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CHEMICAL INHIBITORS OF SOLUBLE ADENYLYL CYCLASE (sAC)

[0001] This application claims the benefit of U.S. Provisional Patent Application Serial No. 60/537,864, filed January 21, 2004, which is hereby incorporated by reference in its entirety.

[0002] The subject matter of this application was made with support from the National Institutes of Health (Grant Nos. GM62328, HD42060, and HD38722). The U.S. Government may have certain rights in this invention.

FIELD OF THE INVENTION

[0003] The present invention relates to methods of treating a disorder mediated by soluble adenylyl cyclase in a subject by modulating soluble adenylyl cyclase in the subject, as well as methods of treating a disorder mediated by soluble adenylyl cyclase in a subject by administering to a subject an effective amount of a compound that modulates soluble adenylyl cyclase in the subject. The present invention also relates to methods of modulating soluble adenylyl cyclase by contacting eukaryotic cells with a compound that modulates soluble adenylyl cyclase.

BACKGROUND OF THE INVENTION

[0004] cAMP is a nearly ubiquitous second messenger molecule that affects a multitude of cellular functions. In mammalian cells, two classes of adenylyl cyclase generate cAMP. Transmembrane adenylyl cyclases (tmACs) are tethered to the plasma membrane and regulated by heterotrimeric G proteins in response to hormonal stimuli (for review, see Hanoune et al., "Regulation and Role of Adenylyl Cyclase Isoforms," *Annu. Rev. Pharmacol. Toxicol.* 41:145–174 (2001)). A second source of cAMP, the more recently described "soluble" adenylyl cyclase (sAC), resides in discrete compartments throughout the cell (Zippin et al., "Compartmentalization of Bicarbonate-Sensitive Adenylyl Cyclase in Distinct Signaling Microdomains," *FASEB J.* 17:82–84 (2003)) and is regulated by the intracellular signaling molecules, bicarbonate (Chen et al., "Soluble Adenylyl Cyclase as an Evolutionarily Conserved Bicarbonate Sensor," *Science*

289:625–628 (2000)) and calcium (Jaiswal et al., "Calcium Regulation of the Soluble Adenylyl Cyclase Expressed in Mammalian Spermatozoa," *Proc. Natl. Acad. Sci. USA* 100:10676–10681 (2003); Litvin et al., "Kinetic Properties of 'Soluble' Adenylyl Cyclase. Synergism Between Calcium and Bicarbonate," *J. Biol. Chem.* 278:15922–15926 (2003)).

[0005] cAMP elicits its cellular effects by activation of three known classes of effector proteins: exchange proteins activated by cAMP (EPAC), cyclic nucleotide gated ion channels, and protein kinase A (PKA). A subset of these targets resides at the plasma membrane, where they exist in macromolecular signaling complexes that also include a G protein coupled receptor, its transducing G protein, and the source of cAMP, a tmAC isoform (Davare et al., "A Beta2 Adrenergic Receptor Signaling Complex Assembled With the Ca^{2+} Channel Cav1.2," *Science* 293:98–101 (2001)). The cAMP generated by tmACs appears to act locally (Rich et al., "Cyclic Nucleotide-Gated Channels Colocalize With Adenylyl Cyclase in Regions of Restricted cAMP Diffusion," *J. Gen. Physiol.* 116:147–161 (2000); Rich et al., "A Uniform Extracellular Stimulus Triggers Distinct cAMP Signals in Different Compartments of a Simple Cell," *Proc. Natl. Acad. Sci. USA* 98:13049–13054 (2001); Zaccolo et al., "Discrete Microdomains With High Concentration of cAMP in Stimulated Rat Neonatal Cardiac Myocytes," *Science* 295:1711–1715 (2002)), most likely restricted by phosphodiesterase "firewalls" (Zaccolo et al., "Discrete Microdomains With High Concentration of cAMP in Stimulated Rat Neonatal Cardiac Myocytes," *Science* 295:1711–1715 (2002); Mongillo et al., "Fluorescence resonance Energy Transfer-Based Analysis of cAMP Dynamics in Live Neonatal Rat Cardiac Myocytes Reveals Distinct Functions of Compartmentalized Phosphodiesterases," *Cir Res* 95(1):65-75 (2004)), which define the limits of these cAMP signaling microdomains. However, targets of cAMP do not solely reside at the plasma membrane. EPAC is localized to the nuclear membrane and mitochondria (Qiao et al., "Cell Cycle-Dependent Subcellular Localization of Exchange Factor Directly Activated by cAMP," *J. Biol. Chem.* 277:26581–26586 (2002)), and PKA is tethered throughout the cell by a class of proteins called AKAP (A-kinase-anchoring proteins; Michel et al., "AKAP Mediated Signal Transduction," *Annu. Rev. Pharmacol. Toxicol.* 42:235–257 (2002)). The observation that cAMP does

not diffuse far from tmACs (Bacskai et al., "Spatially Resolved Dynamics of Camp and Protein Kinase A Subunits in Aplysia Sensory Neurons," *Science* 260:222–226 (1993); Zaccolo et al., "Discrete Microdomains With High Concentration of cAMP in Stimulated Rat Neonatal Cardiac Myocytes," *Science* 295:1711–1715 (2002)) reveals that there must be another source of cAMP modulating the activity of these distally localized targets.

[0006] Soluble adenylyl cyclase (sAC; Buck et al., "Cytosolic Adenylyl Cyclase Defines a Unique Signaling Molecule in Mammals," *Proc. Natl. Acad. Sci. USA* 96:79–84 (1999); U.S. Patent No. 6,544,768 to Buck et al.; International Publication No. WO 01/85753) is widely expressed in mammalian cells (Sinclair et al., "Specific Expression of Soluble Adenylyl Cyclase in Male Germ Cells," *Mol. Reprod. Dev.* 56:6–11 (2000)). Unlike tmACs, sAC is G protein insensitive (Buck et al., "Cytosolic Adenylyl Cyclase Defines a Unique Signaling Molecule in Mammals," *Proc. Natl. Acad. Sci. USA* 96:79–84 (1999)), and among mammalian cyclases, it is uniquely responsive to intracellular levels of bicarbonate (Chen et al., "Soluble Adenylyl Cyclase as an Evolutionarily Conserved Bicarbonate Sensor," *Science* 289:625–628 (2000)). The ubiquitous presence of carbonic anhydrases ensures that the intracellular bicarbonate concentration (and sAC activity) will reflect changes in pH (Pastor-Soler et al., "Bicarbonate-Regulated Adenylyl Cyclase (sAC) is a Sensor That Regulates pH-Dependent V-ATPase Recycling," *J. Biol. Chem.* 278:49523–49529 (2003)) and/or CO_2. Because CO_2 is the end product of energy-producing metabolic processes, sAC is poised to function as a cell's intrinsic sensor of metabolic activity (Zippin et al., "CO(2)/HCO(3)(-)-Responsive Soluble Adenylyl Cyclase as a Putative Metabolic Sensor," *Trends Endocrinol. Metab.* 12:366–370 (2001)). sAC possesses no transmembrane spanning domains (Buck et al., "Cytosolic Adenylyl Cyclase Defines a Unique Signaling Molecule in Mammals," *Proc. Natl. Acad. Sci. USA* 96:79–84 (1999)) and is distributed to subcellular compartments containing cAMP targets (Zippin et al., "Compartmentalization of Bicarbonate-Sensitive Adenylyl Cyclase in Distinct Signaling Microdomains," *FASEB J.* 17:82–84 (2003)) that are distant from the plasma membrane. sAC was also found localized inside the mammalian cell nucleus (Zippin et al.,

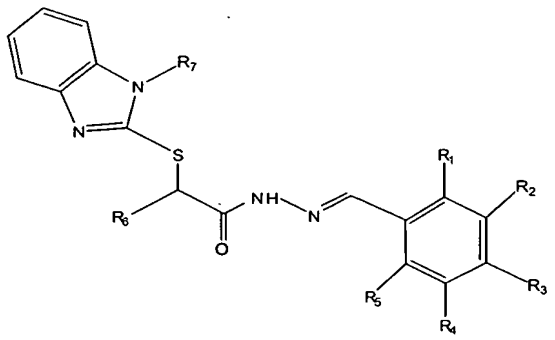
"Compartmentalization of Bicarbonate-Sensitive Adenylyl Cyclase in Distinct Signaling Microdomains," *FASEB J.* 17:82–84 (2003)).

[0007] Although cAMP has been well known as a ubiquitous second messenger molecule affecting many different cellular functions, the source of cAMP in certain cellular processes and its connection to those processes have remained undefined.

[0008] The present invention is directed to overcoming these and other deficiencies in the art.

SUMMARY OF THE INVENTION

[0009] The present invention relates to a method of treating a disorder mediated by soluble adenylyl cyclase in a subject. The method involves administering to a subject an effective amount of a compound that modulates soluble adenylyl cyclase, where the compound has the following formula:



where:

R_1 is H, OH, alkyloxy, or halogen;

R_2 and R_5 are H or halogen;

R_3 is H or OH;

R_4 is H, alkyloxy, or halogen;

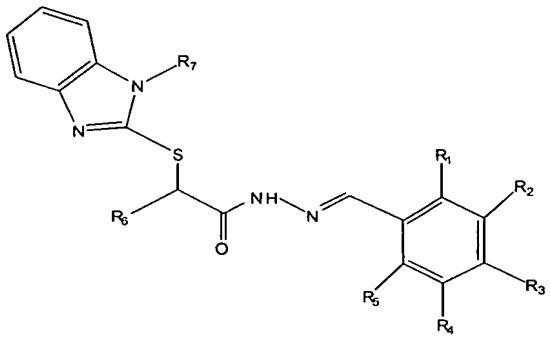
R_6 is H or alkyl; and

R_7 is H or CH_2R_8, where R_8 is H, alkyl, or substituted or unsubstituted phenyl, with the proviso that at least one of R_1, R_2, R_3, and R_4 is a halogen,

under conditions effective to treat the disorder mediated by soluble adenylyl cyclase.

[0010] The present invention also relates to a method of treating a disorder mediated by soluble adenylyl cyclase in a subject, where the disorder is selected from the group consisting of: learning or memory disorders, malaria, fungal infection, spinal cord injury, Alzheimer's disease, amyotrophic lateral sclerosis, and peripheral neuropathy. The method involves modulating soluble adenylyl cyclase in the subject.

[0011] Another aspect of the present invention relates to a method of modulating soluble adenylyl cyclase. The method involves contacting eukaryotic cells with a compound that modulates soluble adenylyl cyclase, where the compound has the following formula:



where:

R_1 is H, OH, alkyloxy, or halogen;

R_2 and R_5 are H or halogen;

R_3 is H or OH;

R_4 is H, alkyloxy, or halogen;

R_6 is H or alkyl; and

R_7 is H or CH_2R_8, where R_8 is H, alkyl, or substituted or unsubstituted phenyl, with the proviso that at least one of R_1, R_2, R_3, and R_4 is a halogen,

under conditions effective to modulate soluble adenylyl cyclase.

[0012] In order to evaluate how sAC-generated cAMP might differ from the second messenger generated by tmACs, a prototypical cAMP-dependent pathway, PKA-dependent phosphorylation of cAMP response element binding protein (CREB; De Cesare et al., "Transcriptional Regulation by Cyclic AMP-Responsive Factors," *Prog. Nucleic Acid Res. Mol. Biol.* 64:343–369 (2000), which is hereby incorporated by reference in its entirety) was investigated. In a

widely accepted signal transduction paradigm, extracellular signals (i.e., hormones and neurotransmitters) affect CREB family phosphorylation by stimulation of plasma membrane–bound tmACs. The generated cAMP activates nearby PKA, and the liberated catalytic subunit then appears to translocate through the cytoplasm to phosphorylate and activate CREB proteins residing inside the nucleus (Riabowol et al., "Microinjection of the Catalytic Subunit of cAMP-dependent Protein Kinase Induces Expression of the c-fos Gene," *Cold Spring Harb. Symp. Quant. Biol.* 53:85–90 (1988); Hagiwara et al., "Coupling of Hormonal Stimulation and Transcription Via the Cyclic AMP-Responsive Factor CREB is Rate Limited by Nuclear Entry of Protein Kinase A," *Mol. Cell. Biol.* 13:4852–4859 (1993), which are hereby incorporated by reference in their entirety). Intracellular signals, such as metabolic activity, also modulate CREB phosphorylation in a cAMP-dependent manner (Daniel et al., "Cyclic AMP Signaling and Gene Regulation," *Annu. Rev. Nutr.* 18:353–383 (1998); Singh et al., "Hexosamine-Induced Fibronectin Protein Synthesis in Mesangial Cells is Associated With Increases in cAMP Responsive Element Binding (CREB) Phosphorylation and Nuclear CREB: The Involvement of Protein Kinases A and C," *Diabetes* 50:2355–2362 (2001); Trumper et al., "Mechanisms of Mitogenic and Anti-Apoptotic Signaling by Glucose-Dependent Insulinotropic Polypeptide in Beta(INS-1)-Cells," *J. Endocrinol.* 174:233–246 (2002), which are hereby incorporated by reference in their entirety), but the mechanism has yet to be established. Localization of sAC inside the nucleus, in close proximity to the CREB family proteins, and its regulation by calcium and bicarbonate suggested that sAC might be responsible for modulating CREB activity in response to intracellular signals.

[0013] The present invention demonstrates the existence of a nuclear cAMP signaling microdomain that mediates bicarbonate-dependent activation of the transcription factor CREB. Bicarbonate activation of CREB represents an example of a mammalian cAMP-dependent pathway solely modulated by intrinsic cellular signals. This nuclear cAMP signaling cascade functions independently from the classically defined mechanisms leading to CREB activation, demonstrating that cAMP is a locally acting second messenger that can work autonomously in different compartments within a single cell.

[0014] Insulin secretion is known to be induced by various nutrient secretagogues: prototypically glucose. In beta-cells of the pancreas, glucose metabolism elicits an increase in cAMP, and substantial evidence implicates the cAMP signaling pathway is essential for glucose-induced insulin release. However, the link between cAMP and glucose metabolism remains unknown. The present invention pharmacologically and genetically identifies this link to be the bicarbonate/calcium-responsive sAC. Furthermore, the present invention shows that, unlike cAMP synthesized by G protein regulated tmACs, sAC generated cAMP is sufficient to elicit insulin release. Consistently, chemical inhibition of sAC in mice induces a diabetes-like phenotype. These results demonstrate that different sources of cAMP act independently and predict that sAC activators would represent a new class of diabetes therapeutic.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] Figures 1A-C show that bicarbonate induces CREB phosphorylation via sAC activation in a PKA-dependent manner. COS7 cells were starved for bicarbonate for 60 min and were either incubated in the same bicarbonate starvation media for an additional 30 min (Figure 1A; No Treatment), incubated in normal, bicarbonate-containing DME in 5% CO_2 for 30 min (Figure 1A; $NaHCO_3$), or preincubated with 10 μM H89 for 10 min followed by incubation in normal, bicarbonate-containing DME in 5% CO_2 for 30 min (Figure 1A; $NaHCO_3$ + H89). As a control, COS7 cells grown in normal DME in 5% CO_2 were incubated with 10 μM of forskolin for 30 min (Figure 1A; Forskolin). Cells were immunostained with phospho-CREB antisera (Figure 1A, right). The images on the left in Figure 1A are phase images of cells on the right. Bar, 50 μm. COS7 cells were transfected with vector control or a 48-kD isoform of sAC, and cells were assayed 36 h after transfection (Figure 1B). Cells were treated with a vehicle control (DMSO) or 10 μM H89 for 10 min and stimulated with 10 μM of forskolin or given vehicle control (DMSO) for an additional 30 min (Figure 1B). Transfected cells were starved for bicarbonate and were either incubated in the same bicarbonate starvation media for an additional 30 min; incubated in normal, bicarbonate-containing DME in 5% CO_2 for 30 min; or preincubated with 10 μM H89 for 10 min followed by incubation in normal,

bicarbonate-containing DME in 5% CO_2 for 30 min (Figure 1C). Top panels in Figures 1B-C show Western blots using anti–phospho-CREB antisera with phosphorylated CREB (P-CREB) protein indicated; the bottom panels show Western blots using CREB-specific antisera with total CREB protein indicated. Shown below the Western blots in Figures 1B-C are the intensities of phospho-CREB relative to CREB normalized to the vector control with no treatment (first lane).

[0016] Figures 2A-B show the time course of CREB phosphorylation by sAC and tmAC. Huh7 cells were starved for 1 h for bicarbonate and CO_2 and incubated in 44 mM of normal, bicarbonate-containing DME in 5% CO_2 for the time indicated (Figure 2A) or kept in normal media and treated with 1 μM PGE_2 for the time indicated (Figure 2B). Top panels in Figures 2A-B show Western blots using anti–phospho-CREB antisera with phosphorylated CREB (P-CREB) protein indicated; the bottom panels show Western blot using CREB-specific antisera with total CREB (CREB) protein indicated. Shown below the Western blots in Figures 2A-B are graphical representations of the intensities of phospho-CREB relative to CREB normalized to the 0 min time point (first lane).

[0017] Figures 3A-D illustrate that immunocytochemistry detects both sAC and PKA in the mammalian cell nucleus. Figure 3A shows confocal immunocytochemistry of Huh7 cells with monoclonal RIIα (top middle) and polyclonal RIα antibody (top right). Top left, To-Pro 3. Overlay of To-Pro 3 with both RIIα and RIα (Figure 3A; bottom left), RIIα (Figure 3A; bottom middle), and RIα (Figure 3A; bottom right). Secondary controls were negative. Figures 3B-C show confocal images of suspension HeLa cells immunostained with PKA regulatory subunit RIIα polyclonal antisera (Figure 3B) and PKA regulatory subunit RIα mAb (Figure 3C). In Figures 3B-C, arrows labeled A and B indicate suspension HeLa cytoplasm. Secondary controls were negative (insets). Figure 3D shows confocal immunocytochemistry of Huh7 cells stained with R41 mAb against sAC.

[0018] Figures 4A-B illustrate that activated CREB, sAC, and PKA are present within the same rat liver nuclei. Figure 4A shows rat liver section stained with DAPI (top left, DNA), R52 biotinylated mAb (top middle, sAC), and

polyclonal RIIα antisera (top right, RIIα); overlays of RIIα and sAC (bottom left), sAC and DAPI (bottom middle), and RIIα and DAPI (bottom right). Arrows labeled A indicate nuclei enriched for both sAC and PKA, whereas arrows labeled B indicate nuclei not enriched for either. Figure 4B shows rat liver section stained with DAPI (top left, DNA), R21 mAb (top middle, sAC), and polyclonal P-CREB antisera (top right, P-CREB); overlays of P-CREB and sAC (bottom left), sAC and DAPI (bottom middle), and P-CREB and DAPI (bottom right). Arrows labeled A indicate nuclei enriched for both sAC and P-CREB, whereas arrows labeled B indicate nuclei enriched for neither. Rat liver tissue immunolocalization was confirmed to be inside the nucleus by confocal microscopy.

[0019] Figures 5A-E illustrate that sAC, PKA, and CREB coexist in mammalian cell nuclei. Figure 5A shows Western blots of cell equivalents from HeLa whole cells (WC), low speed supernatant (S1), and nuclear-enriched high speed pellet (P2) probed with antibodies against NaK ATPase (NaK), histone H1 (Histone), cytochrome oxidase subunit III (COX), and β-tubulin (Tubulin). Figure 5B shows immunocytochemistry of nuclei isolated from HeLa cells (P2 pellet) using CREB polyclonal antisera (Figure 5B; CREB) and sAC R52 biotinylated mAb (Figure 5B; sAC). Differential interference contrast microscopy (Figure 5B; DIC) and 4'-6-Diamidino-2-phenylindole (Figure 5B; DAPI) images shown. Bar, 10 μm. Nuclei isolated from HeLa cells (P2 pellet) immunostained with polyclonal antisera (Figure 5C; Polyclonal) and mAb (Figure 5C; Monoclonal) directed against both RIα and RIIα indicated that both proteins maintained their nucleoplasmic architecture throughout the fractionation procedure. Bottom row in Figure 5C represents staining with goat anti-rabbit (middle) or goat anti-mouse controls (right) alone. Left column in Figure 5C represents DAPI images (Figure 5C; DAPI). Bars, 10 μm. Figure 5D shows a Western blot of nuclear enriched P2 for sAC with R21 mAb. Figure 5E shows Western blots of nuclear enriched P2 pellet with monoclonal (mRIα) and polyclonal (pRIα) antisera against RIα and with monoclonal (mRIIα) and polyclonal (pRIIα) antisera against RIIα. All Westerns blots resolved only single bands of the predicted molecular mass.

[0020] Figures 6A-D illustrate that isolated nuclei contain a bicarbonate-responsive cAMP signaling microdomain dependent on both sAC and PKA. Equal aliquots of nuclei-enriched P2 were incubated with 40 mM NaCl (Basal), 10 μM forskolin (FSK), 1 mM 8-Br cAMP (cAMP), or 40 mM of sodium bicarbonate ($NaHCO_3$) for 10 min, smeared on a chilled glass slide, placed at -20°C, and immunostained for CREB family member phosphorylation using phospho-CREB–specific polyclonal antisera (Figures 6A-B). Intact nuclei were confirmed by DAPI staining (Figure 6A; left). Figure 6A (bottom right) highlights representative nuclei considered positive for CREB phosphorylation for quantitation. Three microscopic fields per condition were photographed and counted by a blinded scientist (Figure 6B). Values graphed in Figure 6B represent the percentage of positive nuclei normalized to Basal (control) averaged from five separate experiments. Ratios above each bar in Figure 6B represent the total number of positive nuclei divided by the total number of nuclei counted for all five experiments. Figure 6C shows a Western blot using phospho-CREB–specific antisera against equal aliquots of nuclei-enriched P2 treated with Mg^{2+}-ATP alone (Basal) or substrate in the presence of 1 mM 8-Br cAMP (cAMP), 40 mM bicarbonate, or 40 mM bicarbonate in the presence of either 10 μM H-89 or 1 mM 8-Br-RpcAMPs. Each band was quantitated and normalized to basal; the relative intensities are basal (1 U), cAMP (30 U), bicarbonate alone (– ; 27 U), bicarbonate plus H-89 (13 U), and bicarbonate plus Rp-cAMPs (8 U). Figure 6D shows a Western blot using phospho-CREB–specific antisera against equal aliquots of nuclei-enriched P2 treated with 10 μM forskolin (FSK) or with 40 mM of bicarbonate alone ($+HCO_3$) or in the presence of 50 μM of a sAC specific inhibitor, KH7 ($+HCO_3$ +KH7).

[0021] Figures 7A-D demonstrate that sAC is present in the Islets of Langerhans and is localized to insulin secretory granules in beta-cells. Figure 7A shows a rat pancreatic islet immunostained with biotinylated anti-sAC monoclonal antibody R52b (left) and anti-insulin (middle) with overlay (right). Figure 7B shows a betaTC6 insulinoma cell (DIC image, first image from left) stained with anti-C-term sAC polyclonal (second image from left), anti-insulin (third image from left), and overlay (fourth image from left). Figure 7C shows RINm5F insulinoma cells (DIC image, first image from left) stained with anti-C-term sAC

polyclonal (second image from left), anti-insulin (third image from left), and overlay (fourth image from left). Figure 7D shows an INS-1E insulinoma cell stained with DAPI (first image from left), anti-sAC biotinylated monoclonal antibody R52b (second image from left), anti-insulin (third image from left), and overlay (fourth image from left). Scale bars indicated.

[0022] Figures 8A-C illustrate that the P site inhibitor, 2'5'ddAdo, is a potent inhibitor of tmACs but is inert towards sAC. Figure 8A shows bicarbonate/calcium stimulated pure sAC protein in the presence of indicated concentrations of the P site inhibitor, 2'5'ddAdo (μM). Figure 8B shows 15 minute cAMP accumulation in intact INS-1E cells in the absence of any stimulator (Basal, white bar) or in the presence of 10 μM Forskolin in the absence (Forskolin, lightly shaded bar) or presence (Forskolin + P site, darkly shaded bar) of 50 μM 2'5'ddAdo. Figure 8C shows adenylyl cyclase activity in INS-1E cell lysate in the absence of any stimulator (Basal, white bar) or in the presence of 10 μM Forskolin in the absence (Forskolin, lightly shaded bar) or presence (Forskolin + P site, darkly shaded bar) of 50 μM 2'5'ddAdo.

[0023] Figures 9A-C illustrate that KH7 differentiates between sAC and tmAC generated cAMP. *In vitro* cyclase activity of purified recombinant sAC in the presence of bicarbonate (40 mM) and calcium (0.5 mM) (Figures 9A-B) or INS-1E cell lysate stimulated by forskolin (10 μM) (Figure 9C) in the presence of the indicated concentrations of KH7 (open squares, μM) (Figures 9A and 9C) or KH7.15 (closed diamonds, μM) (Figures 9B-C).

[0024] Figures 10A-F illustrate that sAC generated cAMP is necessary for glucose-stimulated insulin secretion (GSIS). Figure 10A shows GSIS (measured over 30 minutes) in the presence of 2.5 mM glucose (light square) or 16 mM glucose (dark squares) with indicated concentrations of KH7 (μM). Shown is a representative figure performed at least three times; values represent averages of duplicate determinations ± standard deviation (SD). Insulin secreted (Figure 10B) and intracellular cAMP levels (Figure 10C) were determined from the same wells (n=6) incubated in low glucose (2.5 mM, light bars) or high glucose (16 mM, dark bars) in the presence of vehicle (-), 30 μM KH7 (7), 30 μM KH7.15 (7.15), 50 μM 2-hydroxyestradiol (2OH), or 50 μM 2'5'ddAdo (Psite). Values represent mean ±

standard error of the mean (SEM). ANOVA analysis was performed with asterisks indicating statistical significance as compared to the relevant vehicle control values, except where otherwise noted by a bar above the graph. Figure 10D shows GSIS (i.e., insulin released in the presence of 16 mM glucose) from INS-1E cells over 15 minutes in the presence of vehicle (DMSO), 30 μM KH7 (KH7), or 50 μM 2'5'ddAdo (Psite) with ("+", dark bars) or without ("-", light bars) 0.5 mM IBMX. Values represent mean ± SEM (n=4). ANOVA analysis was performed, with asterisks indicating statistical significance as compared to vehicle control value (- IBMX). Figure 10E shows insulin secreted over 15 minutes in the presence of 2.5 mM (light bar) or 16 mM glucose (dark bars) in the presence of 50 μM KH7 (KH7) or KH7 and 1 mM 8-Br-SpcAMP (KH7 + cAMP). Shown is a representative figure repeated multiple times; values are averages from duplicate determinations ± SD. Figure 10F shows insulin released from mouse islets cultured in low glucose (2.8 mM, light bars) or high glucose (16.7 mM, dark bars) for 30 minutes in the presence of vehicle (DMSO), 30 μM KH7 (KH7), or 30 μM KH7.15 (KH7.15). Values represent mean ± SEM (n=3). ANOVA analysis was performed, with asterisks indicating statistically significant differences. For all graphs, * = $p<0.05$; ** = $p<0.01$; *** = $p<0.001$; and ns = no statistically significant difference.

[0025] Figure 11 illustrates that the catechol estrogen 2-hydroxyestradiol (2OH) inhibited GSIS in INS-1E insulinoma cells. The figure shows 15 minute insulin release from INS-1E cells incubated in low glucose (2.5 mM, lightly shaded bar) or high glucose (16 mM) with indicated concentrations of 2-hydroxyestradiol (2OH; first five darkly shaded bars from the left), KH7 (30 μM; sixth darkly shaded bar from the left) or KH7.15 (30 μM; seventh darkly shaded bar from the left). Shown is a representative experiment repeated at least twice; values represent averages of duplicate determinations with standard deviations indicated.

[0026] Figures 12A-B show that sAC-specific RNA*i* blunts glucose-induced cAMP generation and insulin release. Figure 12A shows intracellular cAMP generated in low (2.5 mM, light bars) or high glucose (16 mM, dark bars) in INS-1E cells transfected with negative control RNA*i* oligos (control) or two different RNA*i* oligonucleotides directed against sAC (sAC #1 and sAC #2).

Shown is a representative figure; values represent duplicate transfected wells. Inset shows representative Western blots of INS-1E cells transfected with the indicated RNA*i* oligonucleotides using anti-sAC (monoclonal antibody R21) or anti-β actin antibody. Figure 12B shows insulin released (over 30 minutes) in low glucose (2.5 mM, light bars) or high glucose (16 mM, dark bars) from cells transfected with the indicated RNA*i* oligonucleotides. Shown is the average fold insulin released in high glucose relative to insulin released in low glucose from eight (8) independently transfected wells. To facilitate comparisons between transfections, all data were first normalized to the average insulin released in low glucose from the combined control transfected wells. Values represent mean ± SEM (n=8). ANOVA analysis was performed with asterisks indicating statistically significant differences. ** = $p<0.01$.

[0027] Figures 13A-B demonstrate that KH7 does not affect PMA induced insulin release or transferrin recycling in INS-1E cells. Figure 13A shows PMA (300 nM) stimulated insulin release (2.5 mM glucose) for 30 minutes in the presence of DMSO or KH7 (30 μM). Values are mean ± SEM (n=3). Data represents fold insulin released over insulin released in low glucose (basal). Figure 13B shows transferrin recycling over 30 minutes in the presence of DMSO (squares) or KH7 (30 μM; diamonds). Shown is a representative experiment repeated at least three times. Data points represent averages of duplicate determinations with error bars indicating standard deviation.

[0028] Figures 14A-C illustrate that sAC-generated cAMP, distinct from tmAC-generated cAMP, is sufficient to elicit insulin secretion. Figure 14A shows cAMP accumulation (top) and insulin secretion (bottom) over 15 minutes in INS-1E cells in low glucose (2.5 mM) alone (lightly shaded bars) or after stimulation with 10 nM glucagon (darkly shaded bars). Shown is a representative assay repeated at least five times; values indicate duplicate determinations with standard deviations. Figure 14B shows cAMP accumulation (top) and insulin secretion (bottom) in 2.5 mM glucose over 15 minutes in INS-1E cells (open bars), SF2 cells (lightly shaded bars), or SF5 cells (darkly shaded bars). Shown is a representative assay repeated at least five times; values indicate duplicate determinations with standard deviations. Insert is a Western blot indicating the levels of sAC protein in INS-1E, SF2, and SF5 cells. Figure 14C shows insulin

secretion from INS-1E or SF2 after incubation for 15 minutes in either 2.5 mM (light bars) or 16 mM glucose (dark bars) in the presence or absence of 30 μM KH7. Values represent mean ± SEM (n=3). ANOVA analysis was performed with asterisks indicating statistically significant differences. *** = $p<0.001$.

[0029] Figures 15A-B illustrate that KH7 inhibits glucose tolerance and insulin release in C57BL/6 mice. Figures 15A-B show serum glucose (n=8) (Figure 15A) and insulin levels (n=5) (normalized to basal) (Figure 15B) in mice at the indicated times, following i.p. glucose injection (1 g/kg) into animals pretreated with 100 μmoles/kg [49 mg/kg] KH7 (open triangles) or DMSO vehicle control (closed squares). Values represent mean ± SEM. Repeated measures ANOVA analysis was performed with asterisks indicating statistical significance of KH7 treatment as compared to vehicle at the time point indicated. For all graphs, * = $p<0.05$; ** = $p<0.01$; and *** = $p<0.001$.

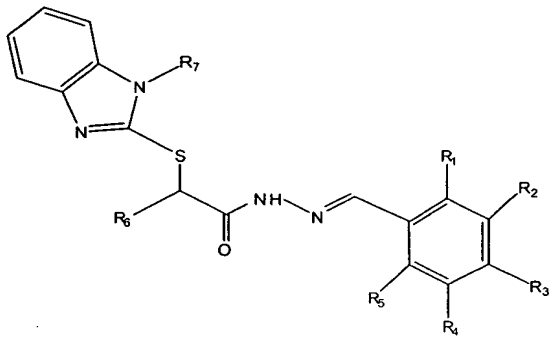
[0030] Figures 16A-B illustrate plasmodium viability (Figure 16A) and cyclase activity (Figure 16B) in the presence of KH7 and KH7.15. Plasmodium cultures were incubated in the indicated concentrations of KH7 or KH7.15 for 24 hours and viability assessed by luciferase assay (Figure 16A). Adenylyl cyclase activity in whole cell extract of isolated parasites was assayed in the presence of $MnCl_2$ and ATP and the indicated concentrations of KH7 or KH7.15 (Figure 16B).

[0031] Figures 17A-B illustrate that the catalytic portion of the sAC-like adenylyl cyclase from *Candida albicans* (fragment JR3) is bicarbonate responsive and KH7 sensitive. Figure 17A depicts the bicarbonate activation of JR3, while Figure 17B shows the KH7 inhibition of JR3.

[0032] Figure 18 illustrates that NGF induced Rap1 activation is blocked by KH7 and rescued by membrane permeable cAMP. PC12 cells were stimulated with or without nerve growth factor (NGF) for 15 minutes in the presence or absence of KH7 (50 μM) and 1 mM 8Br-cAMP. Top panel shows activated Rap1 (GTP bound Rap1) isolated from whole cell extracts by "pull-down" with Rap-GTP binding domain of RalGDS; bottom panel shows total Rap1 in extract (both GTP bound and GDP bound) as control.

DETAILED DESCRIPTION OF THE INVENTION

[0033] The present invention relates to a method of treating a disorder mediated by soluble adenylyl cyclase in a subject. The method involves administering to a subject an effective amount of a compound that modulates soluble adenylyl cyclase, where the compound has the following formula:



where:

R_1 is H, OH, alkyloxy, or halogen;

R_2 and R_5 are H or halogen;

R_3 is H or OH;

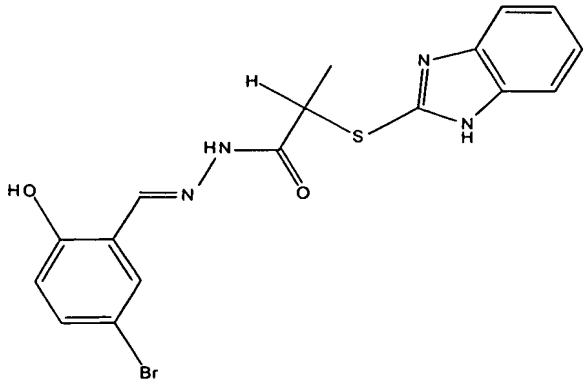
R_4 is H, alkyloxy, or halogen;

R_6 is H or alkyl; and

R_7 is H or CH_2R_8, where R_8 is H, alkyl, or substituted or unsubstituted phenyl, with the proviso that at least one of R_1, R_2, R_3, and R_4 is a halogen,

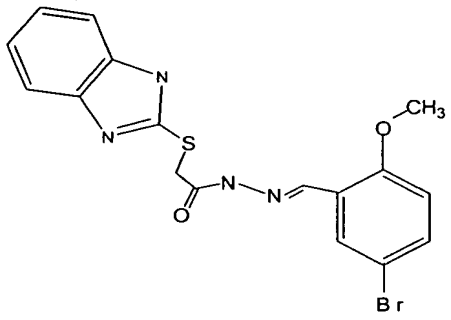
under conditions effective to treat the disorder mediated by soluble adenylyl cyclase. In one embodiment of the present invention, the compound inhibits soluble adenylyl cyclase. In another embodiment, the compound activates soluble adenylyl cyclase.

[0034] In another embodiment of the present invention, the compound has the following formula:



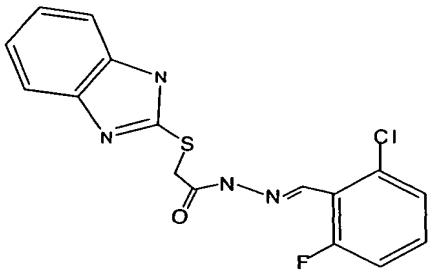
KH7

[0035] In another embodiment, the compound has the following formula:



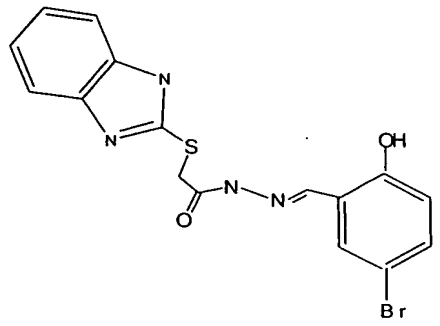
KH7.05

[0036] In another embodiment, the compound has the following formula:



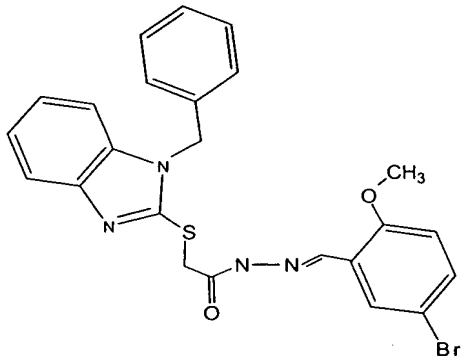
KH7.06

[0037] In another embodiment, the compound has the following formula:



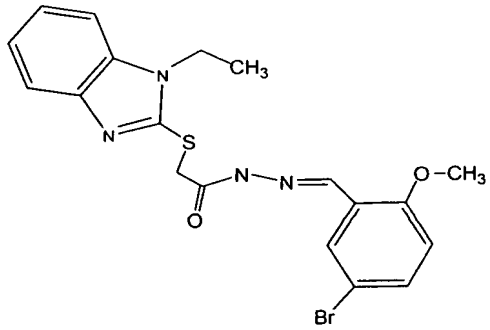
KH7.07

[0038] In another embodiment, the compound has the following formula:



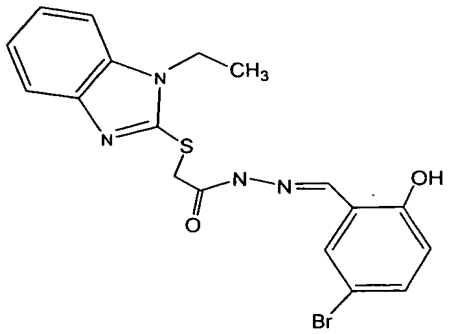
KH7.11

[0039] In another embodiment, the compound has the following formula:



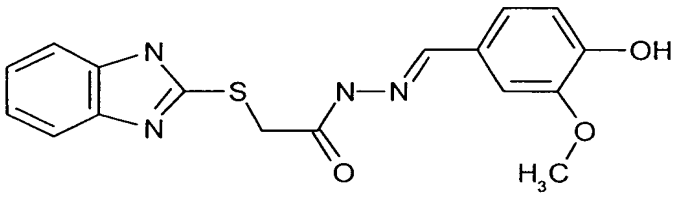
KH7.12

[0040] In another embodiment, the compound has the following formula:



KH7.13

[0041] In yet another embodiment, the compound has the following formula:



KH7.15

[0042] Suitable examples of disorders that are mediated by soluble adenylyl cyclase include, but are not limited to: learning or memory disorders, male fertility/sterility (Chen et al., "Soluble Adenylyl Cyclase as an Evolutionarily Conserved Bicarbonate Sensor," *Science* 289:625–628 (2000); Esposito et al., "Mice Deficient for Soluble Adenylyl Cyclase Are Infertile Because of a Severe Sperm-Motility Defect," *Proc. Natl. Acad. Sci. USA* 101:2993–2998 (2004), which are hereby incorporated by reference in their entirety), glaucoma (Sun et al., "HCO_3^--Dependent Soluble Adenylyl Cyclase Activates Cystic Fibrosis Transmembrane Conductance Regulator in Corneal Endothelium," *Am J Physiol Cell Physiol* 284: C1114–C1122 (2003), which is hereby incorporated by reference in its entirety), metabolic acidosis/alkalosis, diabetes, metabolic disorders, breathing disorders (Sun et al., "HCO_3^--Dependent Soluble Adenylyl Cyclase Activates Cystic Fibrosis Transmembrane Conductance Regulator in Corneal Endothelium," *Am J Physiol Cell Physiol* 284: C1114–C1122 (2003),

which is hereby incorporated by reference in its entirety), insulin resistance, hyperinsulinemia, malaria, fungal infection, spinal cord injury, Alzheimer's disease, amyotrophic lateral sclerosis, and peripheral neuropathy.

[0043] The compounds of the present invention may be orally administered, for example, with an inert diluent, or with an assimilable edible carrier, or they may be enclosed in hard or soft shell capsules, or they may be compressed into tablets, or they may be incorporated directly with the food of the diet. For oral therapeutic administration, these active compounds may be incorporated with excipients and used in the form of tablets, capsules, elixirs, suspensions, syrups, and the like. Such compositions and preparations should contain at least 0.1% of the active compound. The percentage of the compound in these compositions may, of course, be varied and may conveniently be between about 2% to about 60% of the weight of the unit. The amount of active compound in such therapeutically useful compositions is such that a suitable dosage will be obtained.

[0044] The tablets, capsules, and the like may also contain a binder, such as gum tragacanth, acacia, corn starch, or gelatin; excipients, such as dicalcium phosphate; a disintegrating agent, such as corn starch, potato starch, alginic acid; a lubricant, such as magnesium stearate; and a sweetening agent, such as sucrose, lactose, or saccharin. When the dosage unit form is a capsule, it may contain, in addition to materials of the above type, a liquid carrier, such as a fatty oil.

[0045] Various other materials may be present as coatings or to modify the physical form of the dosage unit. For instance, tablets may be coated with shellac, sugar, or both. A syrup may contain, in addition to the active ingredient, sucrose as a sweetening agent, methyl and propylparabens as preservatives, a dye, and flavoring, such as a cherry or orange flavor.

[0046] These active compounds may also be administered parenterally. Solutions or suspensions of these active compounds can be prepared in water suitably mixed with a surfactant, such as hydroxypropylcellulose. Dispersions can also be prepared in glycerol, liquid polyethylene glycols, and mixtures thereof in oils. Illustrative oils are those of petroleum, animal, vegetable, or synthetic origin, for example, peanut oil, soybean oil, or mineral oil. In general, water, saline, aqueous dextrose and related sugar solution, and glycols, such as propylene glycol

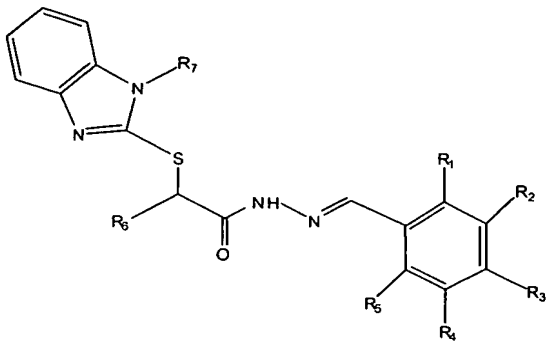
or polyethylene glycol, are preferred liquid carriers, particularly for injectable solutions. Under ordinary conditions of storage and use, these preparations contain a preservative to prevent the growth of microorganisms.

[0047] The pharmaceutical forms suitable for injectable use include sterile aqueous solutions or dispersions and sterile powders for the extemporaneous preparation of sterile injectable solutions or dispersions. In all cases, the form must be sterile and must be fluid to the extent that easy syringability exists. It must be stable under the conditions of manufacture and storage and must be preserved against the contaminating action of microorganisms, such as bacteria and fungi. The carrier can be a solvent or dispersion medium containing, for example, water, ethanol, polyol (e.g., glycerol, propylene glycol, and liquid polyethylene glycol), suitable mixtures thereof, and vegetable oils.

[0048] The compounds of the present invention may also be administered directly to the airways in the form of an aerosol. For use as aerosols, the compounds of the present invention in solution or suspension may be packaged in a pressurized aerosol container together with suitable propellants, for example, hydrocarbon propellants like propane, butane, or isobutane with conventional adjuvants. The materials of the present invention also may be administered in a non-pressurized form, such as in a nebulizer or atomizer.

[0049] The present invention also relates to a method of treating a disorder mediated by soluble adenylyl cyclase in a subject, where the disorder is selected from the group consisting of: learning or memory disorders, malaria, fungal infection, spinal cord injury, Alzheimer's disease, amyotrophic lateral sclerosis, and peripheral neuropathy. The method involves modulating soluble adenylyl cyclase in the subject.

[0050] Another aspect of the present invention relates to a method of modulating soluble adenylyl cyclase. The method involves contacting eukaryotic cells with a compound that modulates soluble adenylyl cyclase, where the compound has the following formula:



where:

R_1 is H, OH, alkyloxy, or halogen;

R_2 and R_5 are H or halogen;

R_3 is H or OH;

R_4 is H, alkyloxy, or halogen;

R_6 is H or alkyl; and

R_7 is H or CH_2R_8, where R_8 is H, alkyl, or substituted or unsubstituted phenyl, with the proviso that at least one of R_1, R_2, R_3, and R_4 is a halogen,

under conditions effective to modulate soluble adenylyl cyclase.

EXAMPLES

[0051] The following examples are provided to illustrate embodiments of the present invention but are by no means intended to limit its scope.

Example 1 – Cell Growth and Transfections

[0052] All cell lines were grown in DME (44 mM sodium bicarbonate) supplemented with 10% FBS. Where indicated, cells were transfected using Lipofectamine 2000 (Invitrogen, Carlsbad, CA) as per the manufacturer's instructions. Cells were incubated with DNA for 5 h in OPTI-MEM (Invitrogen), and then switched to normal media. Bicarbonate starvation was conducted by changing media to bicarbonate-free DME (44 mM Hepes) supplemented with 10% FBS for at least 1 h at 37°C under ambient air conditions. Bicarbonate stimulation consisted of returning cells to normal bicarbonate-containing media and placing them in a 5% CO_2 incubator. For PGE_2 or forskolin stimulation, cells were grown in normal media under 5% CO_2. Stimulation was accomplished by replacing media with normal media containing 1 μM PGE_2 or 10 μM forskolin.

For Western analysis, cells were lysed immediately by direct addition of SDS sample buffer.

Example 2 – Immunocytochemistry

[0053] Cells or nuclei were washed in PBS and fixed for either 30 min in 4% PFA and permeabilized in 0.1% Triton X-100 or fixed for 15 min in 2% PFA and permeabilized in 0.05% Triton X-100. Liver from adult rat was rapidly excised, placed between two thinly sliced pieces of bovine liver, and snap frozen in isopentane cooled with liquid nitrogen. 6-μM-thick cryosections were collected on superfrost slides (Fisher Scientific, Hampton, NH) and stained within 1 day of sectioning. Tissue was fixed for 30 min in 4% PFA and permeabilized in 0.1% Triton X-100 for 15 min. All samples were blocked in 2% BSA for at least 1 h. Cells or tissues were stained with anti-sAC R41 or R52 biotinylated mAbs or R21 mAb (1:100) generated against human 48-kD isoform of sAC (sAC_t) antigen as described previously (Zippin et al., "Compartmentalization of Bicarbonate-Sensitive Adenylyl Cyclase in Distinct Signaling Microdomains," *FASEB J.* 17:82–84 (2003), which is hereby incorporated by reference in its entirety), anti-PKA regulatory subunit (RIα and RIIα) polyclonal antisera (1:100; Chemicon, Temecula, CA, and Cedarlane Laboratories Limited, Hornby, Ontario, Canada) or mAbs (Becton Dickinson, Franklin Lakes, NJ), and anti-CREB or anti–phospho-CREB polyclonal antisera (1:500; Cell Signaling Technologies, Beverly, MA) overnight in 2% BSA, 0.01% Triton X-100; washed three times for 10 min each in 2% BSA, 0.01% Triton X-100; stained for 1 h at room temperature with goat anti–rabbit Alexa Fluor 488, goat anti–mouse Alexa Fluor 568, or goat anti–mouse Alexa Fluor 594 (Molecular Probes, Eugene, OR); treated with 4'-6-Diamidino-2-phenylindole (DAPI) for 5 min or To-Pro 3 (1:500; Molecular Probes) for 15 min; and washed and mounted with gelvatol/DABCO (Sigma-Aldrich, St. Louis, MO).

[0054] For phospho-CREB immunolocalization, cells or nuclei were fixed in 4% PFA for 30 min, permeabilized in 0.1% Triton X-100 for 15 min, blocked for at least 1 h in 3% BSA, and immunostained using phospho-CREB polyclonal antisera (1:500; Cell Signaling Technologies) overnight at 4°C. Staining was visualized by incubation with goat anti–rabbit Alexa Fluor 488 (Molecular Probes) for 1 h at room temperature, treated with DAPI for 5 min, and washed and

mounted with gelvatol/DABCO (Sigma-Aldrich). Fluorescent images were recorded by a digital camera (Hamamatsu, Bridgewater, NJ) connected to an inverted epifluorescent microscope (Nikon, Melville, NY). Images were taken at the same exposure time and gain, and all photographic manipulations were performed equally. Phospho-CREB–positive nuclei were quantified in multiple fields from each stained slide by a blinded experimenter.

[0055] Confocal images were acquired with a confocal system (model LSM 510; Carl Zeiss MicroImaging, Inc., Chester, VA). Goat anti–rabbit Alexa Fluor 488 was excited with a 488-nM Kr/Ar laser, goat anti–mouse Alexa Fluor 568 was excited with a 568-nm Kr/Ar laser, and To-Pro 3 was excited with a 633-nm Kr/Ar laser.

Example 3 – Isolation of Nuclei

[0056] Nuclei were isolated by cellular lysis followed by differential centrifugation (Spector et al. (eds.), "Culture and Biochemical Analysis of Cells," in *Cells: A Laboratory Manual, Vol.1* Cold Spring Harbor Laboratory Press, Cold Spring Harbor, NY (1998), which is hereby incorporated by reference in its entirety) through OptiPrep (Axis-Shield, Oslo, Norway). HeLa cells grown in suspension were lysed by detergent treatment in TM-2 buffer (0.01 M Tris-HCl, pH 7.4, 1.5 mM $MgCl_2$, 150 mM NaCl, 0.5 mM PMSF, 10 μg/ml apoprotin, and 10 μg/ml leupeptin) containing 100 μg/ml of digitonin followed by a 1,000-*g* spin. Supernatant (S1) was removed and the pellet was resuspended in 0.25 M sucrose, 25 mM KCl, 30 mM $MgCl_2$, and 20 mM Tris-HCl, pH 7.8. The resuspended pellet and 60% OptiPrep iodixanol were mixed (30% OptiPrep final) and centrifuged at 10,000 g for 20 min. The supernatant was removed and the nuclei-enriched pellet (P2) was resuspended in TM-2 buffer without detergent.

Example 4 – CREB Phosphorylation and Adenylyl Cyclase Assays

[0057] Equal aliquots of nuclei-enriched P2 preparations were incubated in 50 μl of the final volume of 100 mM Tris, pH 7.2, 10 mM $MgCl_2$, and 5 mM ATP for CREB phosphorylation and 100 mM Tris, pH 7.2, 10 mM $MgCl_2$, 5 mM ATP, and 0.5 mM IBMX for adenylyl cyclase assay with the indicated additions for 10 min (CREB phosphorylation) or 15 min (adenylyl cyclase) at 37°C.

Reactions were stopped by the addition of 20 µl of SDS sample buffer (CREB phosphorylation) or by being placed into a 100°C heat block for 3 min (adenylyl cyclase).

[0058] For whole cell and isolated nuclei CREB phosphorylation assays, equal cell or nuclear equivalents were separated under reducing conditions using a 10% SDS-PAGE, transferred to a PVDF membrane, and probed for CREB (rabbit polyclonal antiserum; Chemicon, Temecula, CA) and phosphorylated CREB (rabbit polyclonal antiserum; Upstate Biotechnology, Temecula, CA). HRP-conjugated secondary antibodies were used, and bands were visualized using ECL. Image analysis software (model Fluorchem 8800; Alpha Innotech, San Leandro, CA) was used to quantitate Western results. Intensities of phospho-CREB bands were normalized to total CREB.

[0059] cAMP produced in the cyclase assays was detected using a competition-based assay with [^{3}H]cAMP (Amersham Biosciences, Piscataway, NJ) and compared with a cAMP standard curve for quantitation.

[0060] Inhibitor profiles were determined by adenylyl cyclase assay (Assay Designs, Inc., Ann Arbor, MI) using purified sAC protein (Litvin et al., "Kinetic Properties of 'Soluble' Adenylyl Cyclase. Synergism Between Calcium and Bicarbonate," *J. Biol. Chem.* 278:15922–15926 (2003), which is hereby incorporated by reference in its entirety) in the presence of 10 mM $NaHCO_3$, 0.5 mM $CaCl_2$, 10 mM $MgCl_2$, and 10 mM ATP or a mixture of purified catalytic domains, C1 and C2, from Type VII tmAC (Yan et al., "Construction of Soluble Adenylyl Cyclase From Human Membrane-Bound Type 7 Adenylyl Cyclase," *Methods Enzymol.* 345:231–241 (2002), which is hereby incorporated by reference in its entirety) in the presence of 5 mM $MgCl_2$ and 1 mM ATP.

Example 5 – Quantitation of Isolated Nuclei (P2 fraction) Immunocytochemistry

[0061] Nuclei were treated with Mg^{2+}-ATP alone or in combination with bicarbonate, forskolin, or 8-Br-cAMP for 10 min, spread on a chilled slide, stored at -20°C, and immunostained using phospho-CREB–specific antisera. Nuclei were also treated with DAPI to differentiate intact nuclei from membrane ghosts. DAPI-positive nuclei were scored for phosho-CREB immunofluorescence.

Nuclei with detectable staining (Figure 6A, $NaHCO_3$) were considered positive for CREB phosphorylation, whereas nuclei with no detectable staining (Figure 6A, Basal) were counted as negative. Multiple microscopic fields were photographed for each condition, and data was combined from three to five separate experiments.

Example 6 – Western Analysis

[0062] Equal cell equivalents, unless otherwise noted, were separated under reducing conditions using a 10% SDS-PAGE, transferred to PVDF membrane, and blocked in 5% milk. The blots were probed with antibodies against either NaK ATPase (monoclonal, 1:50; Santa Cruz Biotechnology, Inc., Santa Cruz, CA), histone H1 (monoclonal, 1:100; Santa Cruz Biotechnology, Inc.), cytochrome oxidase subunit III (monoclonal, 2 μg/ml; Molecular Probes), β-tubulin (monoclonal, 1:1000; Sigma-Aldrich), sAC (R21 mAb, 1:500), monoclonal RIα or RIIα antibodies (1:250; Becton Dickinson), or polyclonal RIαor RIIα antisera (1:5000; Chemicon) overnight. HRP-conjugated secondary antibodies were used and bands were visualized using ECL.

Example 7 – Bicarbonate Induces CREB Phosphorylation

[0063] Bicarbonate treatment of cells uniquely activates sAC (Chen et al., "Soluble Adenylyl Cyclase as an Evolutionarily Conserved Bicarbonate Sensor," *Science* 289:625–628 (2000), which is hereby incorporated by reference in its entirety), whereas activation by G proteins or forskolin only stimulates tmACs; therefore, these agents can be used to differentially stimulate the two classes of mammalian adenylyl cyclase. To determine whether sAC activation would elicit PKA activation of CREB, a well-characterized target of tmAC-generated cAMP, cells were treated with bicarbonate, and PKA-dependent phosphorylation of CREB was measured using antisera specific for the PKA (Ser133) phosphorylated form of CREB. Hormonal stimulation of CREB transcription factors, acting through tmACs, reaches its peak in 30 min (Hagiwara et al., "Transcriptional Attenuation Following cAMP Induction Requires PP-1-Mediated Dephosphorylation of CREB," *Cell* 70:105–113 (1992), which is hereby incorporated by reference in its entirety). Treatment of COS7 cells with forskolin,

which will activate the total cellular pool of tmACs, stimulated nuclear immunofluorescent staining and Western blot immunoreactivity using the phosphospecific antisera (Figures 1A and 1B). Treatment of COS7 cells for the same amount of time (30 min) with bicarbonate also resulted in CREB phosphorylation (Figures 1A and 1C). These increases in phospho-CREB immunostaining were inhibited by pretreatment with H89, confirming the involvement of PKA (Figures 1A–C). Overexpression of sAC led to an increase in basal CREB phosphorylation (Figures 1B and 1C, fourth lane), suggesting that sAC-generated cAMP was sufficient to activate CREB. Consistent with its bicarbonate responsiveness (Chen et al., "Soluble Adenylyl Cyclase as an Evolutionarily Conserved Bicarbonate Sensor," *Science* 289:625–628. (2000), which is hereby incorporated by reference in its entirety), sAC overexpressing COS7 cells displayed enhanced bicarbonate-dependent CREB phosphorylation (Figure 1C, second and fifth lanes), which was also blocked by H89 (Figure 1C). The ability of either bicarbonate or forskolin to induce CREB phosphorylation revealed that CREB represents a downstream target of both tmAC- and sAC-generated cAMP.

Example 8 – Time Course of Bicarbonate-Induced CREB Phosphorylation

[0064] The time course of CREB activation in response to a hormonal activator of tmACs, PGE_2, was directly compared to the time course of CREB activation in response to specific sAC activator, bicarbonate, in a liver cell line (Hagiwara et al., "Transcriptional Attenuation Following cAMP Induction Requires PP-1-Mediated Dephosphorylation of CREB," *Cell* 70:105–113 (1992), which is hereby incorporated by reference in its entirety). Phosphorylation of CREB in response to bicarbonate occurred rapidly; increases in phospho-CREB were detected within 2 min, the earliest time tested (Figure 2A). In contrast, PGE_2 (Figure 2B) or forskolin stimulation of CREB phosphorylation was detectable only after 5 min, consistent with published papers (Hagiwara et al., "Transcriptional Attenuation Following cAMP Induction Requires PP-1-Mediated Dephosphorylation of CREB," *Cell* 70:105–113 (1992), which is hereby incorporated by reference in its entirety). The longer activation kinetics after PGE_2 or forskolin stimulation may reflect the time required for translocation of

PKA catalytic subunit into the nucleus from the plasma membrane where it is activated by a hormonally modulated tmAC (Hagiwara et al., "Coupling of Hormonal Stimulation and Transcription Via the Cyclic AMP-Responsive Factor CREB is Rate Limited by Nuclear Entry of Protein Kinase A," *Mol. Cell. Biol.* 13:4852–4859 (1993), which is hereby incorporated by reference in its entirety). In addition to being more rapid, the peak intensity of phosphorylation was higher with bicarbonate treatment. The different kinetics and intensity of CREB activation by bicarbonate and PGE_2 revealed that, whereas sAC and tmACs may affect overlapping substrates, they may participate in distinct signal transduction cascades.

Example 9 – CREB, sAC, and PKA Coexist in the Nucleus

[0065] Because CREB family members and sAC (Zippin et al., "Compartmentalization of Bicarbonate-Sensitive Adenylyl Cyclase in Distinct Signaling Microdomains," *FASEB J.* 17:82–84 (2003), which is hereby incorporated by reference in its entirety) reside inside the nucleus, it was reasoned that the accelerated kinetics and intensity of bicarbonate-induced CREB activation could occur if sAC and CREB coexisted in a signal transducing complex. A complete nuclear cAMP signaling cascade capable of phosphorylating CREB family proteins requires the presence of the cAMP-responsive PKA holoenzyme. Both catalytic and regulatory subunits of PKA have been immunologically (Kuettel et al., "Localization of Nuclear Subunits of Cyclic AMP–Dependent Protein Kinase by the Immunocolloidal Gold Method," *J. Cell Biol.* 101:965–975 (1985); Jungmann et al., "Using Immunocolloidal Gold Electron Microscopy to Investigate cAMP-Dependent Protein Kinase Cellular Compartmentalization," *Methods Enzymol.* 159:225–235 (1988); Yang et al., "A-Kinase Anchoring Protein 100 (AKAP100) is localized in Multiple Subcellular Compartments in the Adult Rat Heart," *J. Cell Biol.* 142:511–522 (1998), which are hereby incorporated by reference in their entirety) and biochemically (Byus et al., "Direct Cytochemical Localization of Catalytic Subunits Dissociated from cAMP-Dependent Protein Kinase in Reuber H-35 Hepatoma Cells. II. Temporal and Spatial Kinetics," *J. Cell Biol.* 93:727–734 (1982); Murray et al., "Intracellular Kinetics of Free Catalytic Units Dissociated From Adenosine 3',5'-

Monophosphate-Dependent Protein Kinase in Adrenocortical Tumor Cells (Y-1)," *Endocrinology* 116:364–374 (1985); Zhang et al., "Nuclear Localization of Type II cAMP-Dependent Protein Kinase During Limb Cartilage Differentiation is Associated With a Novel Developmentally Regulated A-Kinase Anchoring Protein," *Dev. Biol.* 176:51–61 (1996); Constantinescu et al., "Ethanol-Induced Translocation of cAMP-Dependent Protein Kinase to the Nucleus. Mechanism and Functional Consequences," *J. Biol. Chem.* 274:26985–26991 (1999), which are hereby incorporated by reference in their entirety) detected inside the nucleus. Nuclear localization of the PKA holoenzyme has been described in lower eukaryotes (Griffioen et al., "Nutritional Control of Nucleocytoplasmic Localization of cAMP-Dependent Protein Kinase Catalytic and Regulatory Subunits in *Saccharomyces cerevisiae*," *J. Biol. Chem.* 275:1449–1456 (2000), which is hereby incorporated by reference in its entirety), but the nuclear presence of the PKA regulatory subunit, and the cAMP-responsive holoenzyme, has been questioned. The immunological examination of regulatory subunit localization was repeated and extended, and it was confirmed that PKA resided inside the nucleus of the human liver cell line Huh7 (Figure 3A), in suspension HeLa cells (Figures 3B-C), and in a subset of cells within sectioned liver tissue (Figure 4A). Confocal microscopy of Huh7 and HeLa cells, using polyclonal and monoclonal antibodies that recognize PKA regulatory subunit isoforms (RIα and RIIα), revealed distinctive cytoplasmic staining in accordance with accepted dogma (Alto et al., "Intracellular Targeting of Protein Kinases and Phosphatases," *Diabetes* 51(3):S385–S388 (2002), which is hereby incorporated by reference in its entirety; Figures 3A-C), but these regulatory subunit isoforms were also detected inside the nucleus (Figures 3A-C and Figure 4A). In the case of suspension HeLa cells, it should be stressed that these optical slices were selected to illustrate the intranuclear staining of PKA. Slide preparation and imaging constraints caused PKA cytoplasmic staining to appear as a thin layer surrounding the nucleus (Figures 3B-C, arrows labeled A) and within the expanse of cytoplasm stretching out as these suspension cells adhere to the coverslip (Figures 3B-C, arrows labeled B).

[0066] Nuclear staining of each isoform was distinct. RIIα was present in a diffuse pattern throughout the nucleus with small areas of enrichment

(Figure 3A, mRIIα; and Figure 3B), whereas RIα was distributed in the nucleoplasm but more enriched in nucleoli (Figure 3A, pRIα; and Figure 3C). RIIα was also detected in the nuclei of a subset of rat liver primary hepatocytes (Figure 4A). Consistent with Zippin et al., "Compartmentalization of Bicarbonate-Sensitive Adenylyl Cyclase in Distinct Signaling Microdomains," *FASEB J.* 17:82–84 (2003), which is hereby incorporated by reference in its entirety, sAC was also present in the nuclei of Huh7 cells (Figure 3D) and a subset of rat liver hepatocytes (Figure 4). PKA, sAC, and phosphorylated CREB seem to be coordinately localized; the subset of nuclei in rat liver hepatocytes and Huh7 cells positive for sAC protein (Figures 4A-B, arrows labeled A) also contained R subunit (Figure 4A, arrows labeled A) and CREB phosphorylation (Figure 4B, arrows labeled A), whereas nuclei not enriched for sAC displayed neither R subunit nor CREB phosphorylation (Figures 4A-B, arrows labeled B). Rat liver hepatocytes positive for sAC, PKA, and phospho-CREB represented ~10% of total hepatocytes, and any consistency with known liver anatomy has not yet been identified. These data demonstrated that nuclei contained all the components of a cAMP signaling cascade and suggested that sAC-generated cAMP is positioned to activate nuclear PKA holoenzymes to phosphorylate CREB proteins.

Example 10 – Isolated Nuclei Contain Components of a cAMP Signaling Microdomain

[0067] Bicarbonate treatment of whole cells led to rapid induction of CREB phosphorylation (Figures 2A-B). To test whether the nuclear localized sAC and PKA were responsible for this bicarbonate-induced CREB activation, isolated nuclei was prepared from suspension HeLa cells, a cell line with well-established protocols for the isolation and enrichment of nuclei. Cells were lysed using digitonin, and nuclear preparations were purified by density centrifugation through an OptiPrep gradient. Western analyses of the same cell equivalents from each fraction, using cellular markers for different subcellular compartments (histone H1, NaK ATPase α1 subunit, cytochrome *c* oxidase subunit III [COX], and β-tubulin) confirmed that the nuclear fractions (P2) were positive for nuclear markers (histone) with undetectable levels of plasma membrane (NaK ATPase), mitochondrial (COX), or cytoplasmic (tubulin) contamination (Figure 5A). To

confirm that the P2 fraction did not contain any detectable mitochondria, a possible source of both sAC and PKA contamination, the P2 fraction was overloaded, but COX antigen was still not detected. Visual inspection and DAPI fluorescence confirmed that the final preparation was enriched for intact nuclei (Figures 5B-C), and, as expected, isolated nuclei contained both CREB and sAC proteins by immunocytochemistry (Figure 5B) and Western blotting (Figure 5D).

[0068] Consistent with the aforementioned staining patterns (Figures 3A-C), RIIα immunostaining was present throughout the nucleus, whereas RIα appeared enriched within the nucleolus (Figure 5C). PKA RIα and RIIα were also detected by Western analysis as a single band of the predicted molecular mass in the P2 lysate, using monoclonal and polyclonal antibodies (Figure 5E), confirming the specificities of these antibodies for immunostaining. Because the staining patterns of isolated HeLa cell nuclei (Figure 5C) reflected the immunostaining pattern observed in intact HeLa cells (Figure 5B-C), it was concluded that the isolation and enrichment of nuclei had little effect on nucleoplasm architecture.

Example 11 – sAC Represents the Only Source of cAMP Detectable in Isolated Nuclei

[0069] Zippin et al., "Compartmentalization of Bicarbonate-Sensitive Adenylyl Cyclase in Distinct Signaling Microdomains," *FASEB J.* 17:82–84 (2003), which is hereby incorporated by reference in its entirety, previously demonstrated that sAC activity was present in COS7 cell nuclei. The results described in Example 10 showed that bicarbonate-responsive sAC was the only source of cAMP in nuclei isolated from suspension HeLa cells. Whereas forskolin potently stimulated cAMP production in whole cell lysates, there was no significant increase in cAMP elicited by forskolin in isolated nuclei. There was a significant level of basal adenylyl cyclase activity in isolated nuclei, which was stimulated by bicarbonate addition. Both the bicarbonate-stimulated and basal activities were inhibited by sAC-selective inhibitors. Several sAC inhibitors (Table 1), inert toward tmACs, were identified in a screen of a combinatorial chemical library. In the presence of representative inhibitors, the cAMP generated in the presence of bicarbonate in P2 nuclei was reduced to a level below that of

basal. These results indicated that, in addition to mediating the bicarbonate-induced increase in cAMP in isolated nuclei, sAC is also responsible for the observed basal adenylyl cyclase activity.

Table 1. Compounds That Modulate sAC Activity *in vitro* and *in vivo*

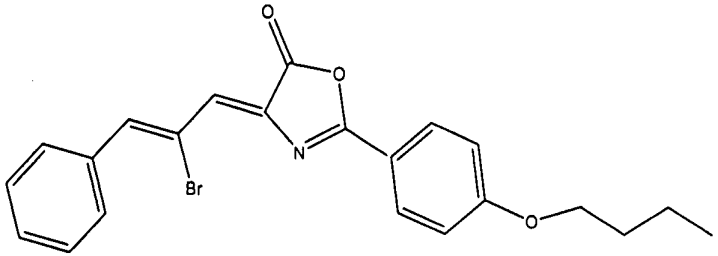
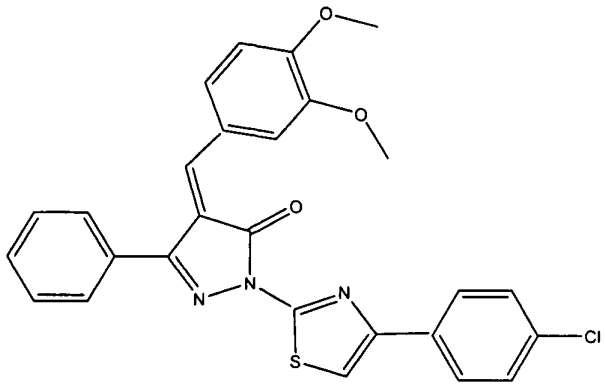
Name	Structure	*in vitro* IC_{50}[a]				*in vivo* IC_{50}[b]	
		pure sAC	pure sol.AC7	sAC in extracts	tmAC in extracts	sAC (basal)	tmAC (FSK)
KH1		23 μM	> 200 μM			> 500 μM	> 500 μM
KH2		2 μM	> 400 μM	>>100	>>100	> 500 μM	> 500 μM

Table 1 (cont'd)

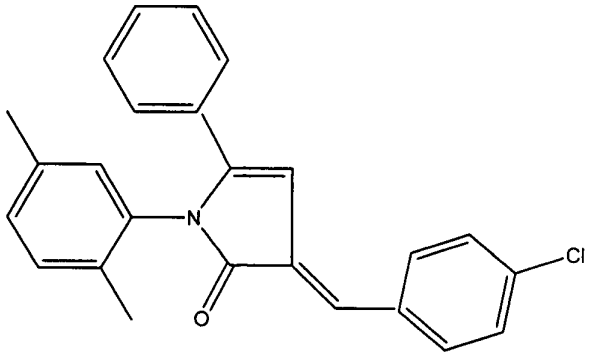
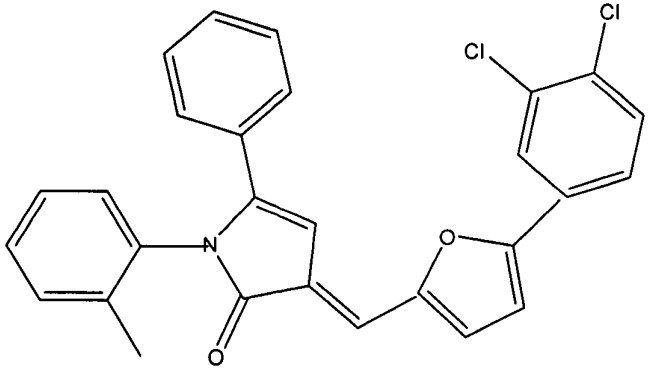
Name	Structure	*in vitro* IC_{50}[a]				*in vivo* IC_{50}[b]	
		pure sAC	pure sol.AC7	sAC in extracts	tmAC in extracts	sAC (basal)	tmAC (FSK)
KH3		8 µM	> 500 µM	>>100	>>100	> 500 µM	> 500 µM
KH4		6 µM	>> 27 µM	>>100	>>100	> 500 µM	> 500 µM

Table 1 (cont'd)

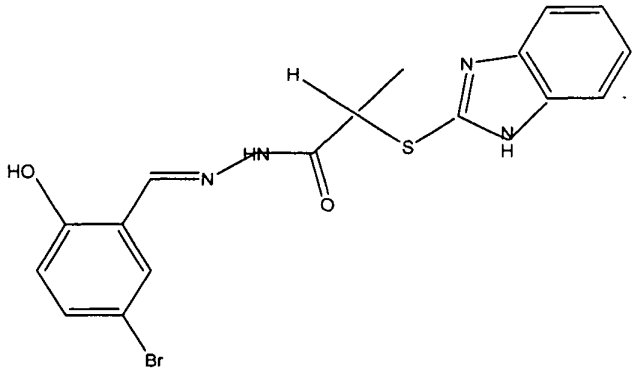
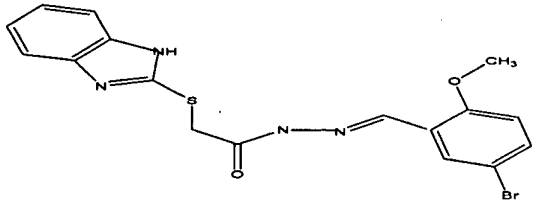
Name	Structure	*in vitro* IC_{50}[a]				*in vivo* IC_{50}[b]	
		pure sAC	pure sol.AC7	sAC in extracts	tmAC in extracts	sAC (basal)	tmAC (FSK)
KH7		1 µM	>> 55 µM	< 10 µM	>> 100 µM	10 µM - 30 µM	> 500 µM
KH7.05		~30				30 µM	>200 µM

Table 1 (cont'd)

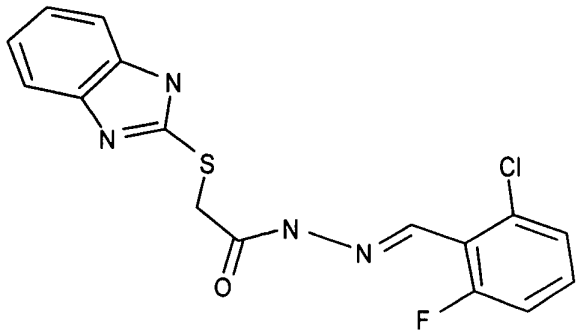
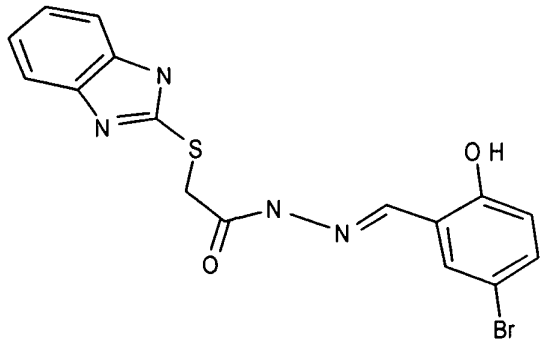
Name	Structure	*in vitro* IC_{50}[a]				*in vivo* IC_{50}[b]	
		pure sAC	pure sol.AC7	sAC in extracts	tmAC in extracts	sAC (basal)	tmAC (FSK)
KH7.06		~30					
KH7.07		30 µM				30 µM	>200 µM

Table 1 (cont'd)

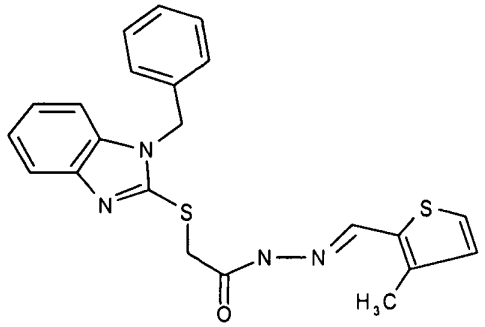
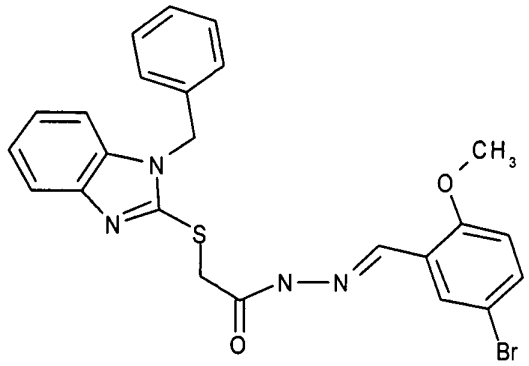
Name	Structure	*in vitro* IC_{50}[a]				*in vivo* IC_{50}[b]	
		pure sAC	pure sol.AC7	sAC in extracts	tmAC in extracts	sAC (basal)	tmAC (FSK)
KH7.10		80					
KH7.11		65					

Table 1 (cont'd)

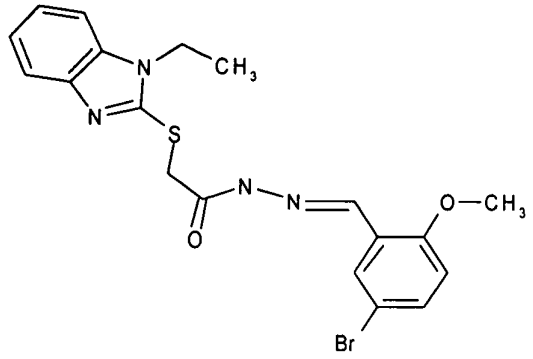
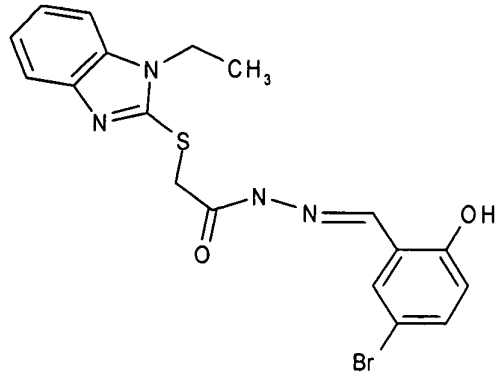
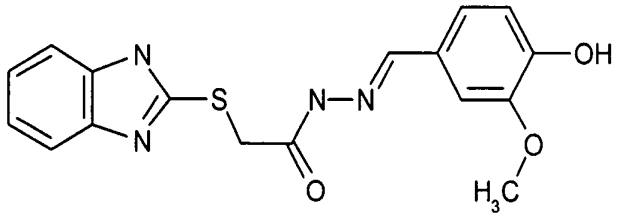
Name	Structure	*in vitro* IC_{50}[a]				*in vivo* IC_{50}[b]	
		pure sAC	pure sol.AC7	sAC in extracts	tmAC in extracts	sAC (basal)	tmAC (FSK)
KH7.12		30					
KH7.13		75					

Table 1 (cont'd)

Name	Structure	*in vitro* IC_{50}[a]				*in vivo* IC_{50}[b]	
		pure sAC	pure sol.AC7	sAC in extracts	tmAC in extracts	sAC (basal)	tmAC (FSK)
KH7.15		~1mM				>200 μM	

[a] *In vitro* IC_{50} refers to the concentration that inhibits 50% of the *in vitro* cyclase activity of purified sperm isoform of sAC protein (pure sAC), purified solubilized version of Type VII tmAC (sol.AC7), whole cell extracts from cells overexpressing sperm sAC cDNA (sAC in extracts), or cells overexpressing Type II tmAC (tmAC in extracts).

[b] *In vivo* IC_{50} refers to the concentration required to inhibit 50% of the cAMP forming activity inside cells stably overexpressing sAC [sAC(basal)] or cells stimulated with forskolin [tmAC (FSK)]. (Forskolin exclusively stimulates tmACs.)

Example 12 – Bicarbonate Induces CREB Phosphorylation in Isolated Nuclei

[0070] CREB phosphorylation in isolated nuclei was assayed by immunocytochemistry using phospho-CREB–specific antisera (Figures 6A-B). Nuclei incubated in the presence of either bicarbonate or cAMP displayed at least a twofold rise in the percentage of phospho-CREB–positive nuclei relative to untreated nuclei (basal; Figure 6B). As expected, due to the lack of tmACs in isolated nuclei, the number of nuclei positive for CREB phosphorylation was unaffected by forskolin. These data demonstrated that a bicarbonate-responsive signaling cascade leading to CREB phosphorylation was wholly contained within the mammalian cell nucleus. In contrast, the hormone and forskolin-responsive tmAC-defined cascade is only functional in a whole cell context.

Example 13 – Nuclear sAC Activates CREB via Nuclear PKA

[0071] To facilitate the use of pharmacological reagents to further evaluate bicarbonate-induced CREB phosphorylation, CREB phosphorylation by Western analysis was monitored (Figures 6C-D). Similar to the observations using immunocytochemistry (described in Example 12), treatment of isolated nuclei with bicarbonate or 8-Br-cAMP elicited a 27- or 30-fold increase in CREB phosphorylation, respectively (Figure 6C). Once again, forskolin, which had a potent effect in a whole cell context (Figure 1), elicited no significant stimulation of CREB phosphorylation in isolated nuclei (Figure 6D).

[0072] Next, it was confirmed that the effects of bicarbonate on CREB phosphorylation were mediated by nuclear sAC and PKA. CREB phosphorylation induced by bicarbonate was substantially reduced by the PKA inhibitors, H89 (50%) and RpcAMPs (70%; Figure 6C), revealing the involvement of cAMP-responsive PKA holoenzyme. A representative chemical inhibitor, KH7, was effective in preventing bicarbonate-induced CREB phosphorylation (Figure 6D), demonstrating, once again, that sAC is responsible for the bicarbonate-stimulated cAMP-dependent phosphorylation of CREB in the mammalian cell nucleus.

Example 14 – Bicarbonate-Responsive sAC Defines a Nuclear cAMP Microdomain

[0073] Most cellular pathways in eukaryotic cells are impacted by cAMP. Effectors of cAMP mediate processes at both the plasma membrane and multiple, distinct intracellular sites. It has been widely assumed that cAMP is generated exclusively at the plasma membrane by G protein–regulated tmACs, and the second messenger then diffuses from the cell membrane through the cytosol to its intracellular targets. However, FRET-based (Bacskai et al., "Spatially Resolved Dynamics of Camp and Protein Kinase A Subunits in Aplysia Sensory Neurons," *Science* 260:222–226 (1993); Zaccolo et al., "Discrete Microdomains With High Concentration of cAMP in Stimulated Rat Neonatal Cardiac Myocytes," *Science* 295:1711–1715 (2002), which are hereby incorporated by reference in their entirety) and biochemical (Rich et al., "Cyclic Nucleotide-Gated Channels Colocalize With Adenylyl Cyclase in Regions of Restricted cAMP Diffusion," *J. Gen. Physiol.* 116:147–161 (2000); Rich et al., "A Uniform Extracellular Stimulus Triggers Distinct cAMP Signals in Different Compartments of a Simple Cell." *Proc. Natl. Acad. Sci. USA* 98:13049–13054 (2001), which are hereby incorporated by reference in their entirety) methods for observing intracellular cAMP concentrations reveal that the second messenger generated by tmACs does not diffuse far from its site of synthesis. It has been recently demonstrated that sAC is localized at multiple, subcellular compartments throughout the cell including mitochondria, centrioles, mitotic spindles, mid-bodies, and nuclei (Zippin et al., "Compartmentalization of Bicarbonate-Sensitive Adenylyl Cyclase in Distinct Signaling Microdomains," *FASEB J.* 17:82–84 (2003), which is hereby incorporated by reference in its entirety), each of which contains targets of cAMP. These data suggest that the cell may contain multiple, independently modulated cAMP signaling microdomains; targets near the plasma membrane would depend on tmACs for second messenger generation, whereas targets inside the cell would be modulated by sAC-generated cAMP (Wuttke et al., "Bicarbonate-Regulated Soluble Adenylyl Cyclase," *JOP* 2:154–158 (2001); Zippin et al., "Compartmentalization of Bicarbonate-Sensitive Adenylyl Cyclase in Distinct Signaling Microdomains," *FASEB J.* 17:82–84 (2003), which are hereby incorporated by reference in their entirety). The data disclosed herein support this

hypothesis by demonstrating the existence of a sAC-defined nuclear cAMP signaling microdomain, which can lead to CREB activation.

[0074] The nuclear cAMP signaling cascade induced by bicarbonate produced a rapid activation of CREB family members in both whole cells and nuclei, whereas PGE_2 and forskolin, tmAC-specific activators, produced a delayed response exclusively in whole cells. Therefore, cAMP-mediated activation of CREB family members by tmACs and sAC proceed via independent pathways. CREB activation by hormones or neurotransmitters via tmACs apparently requires time for movement of PKA catalytic subunit from the plasma membrane into the nucleus (Riabowol et al., "The Catalytic Subunit of cAMP-Dependent Protein Kinase Induces Expression of Genes Containing cAMP-Responsive Enhancer Elements," *Nature* 336:83–86 (1988); Hagiwara et al., "Coupling of Hormonal Stimulation and Transcription Via the Cyclic AMP-Responsive Factor CREB is Rate Limited by Nuclear Entry of Protein Kinase A," *Mol. Cell. Biol.* 13:4852–4859 (1993), which are hereby incorporated by reference in their entirety). This delayed activation is consistent with hormonal control of gene expression providing a long-term response to predominantly sustained extracellular signals (Bailey et al., "Toward a Molecular Definition of Long-Term Memory Storage," *Proc. Natl. Acad. Sci. USA* 93:13445–13452 (1996), which is hereby incorporated by reference in its entirety). In contrast, the newly described nuclear sAC activation pathway proceeds rapidly without requiring the translocation of any constituent. In this regard, the sAC nuclear microdomain is capable of responding quickly to subtle fluctuations in intrinsic signals, such as local intracellular concentrations of bicarbonate and calcium.

[0075] In tissues, sAC is not present within the nucleus of every cell. In liver, sAC appeared to be predominantly extranuclear but enriched in a subset of the nuclei (Figures 4A-B, arrows labeled A). PKA holoenzyme appeared to be enriched within the same subset of nuclei (Figure 4A, arrows labeled A), and interestingly, these are the nuclei that were also positive for CREB phosphorylation (Figure 4B, arrows labeled A). The presence of both positive and negative nuclei for sAC, PKA, and CREB phosphorylation in the same tissue suggests that there may be coordinated regulation of the presence of this newly described nuclear signaling microdomain.

[0076] The demonstration that bicarbonate treatment of whole cells led to activation of the CREB family of transcription factors revealed that bicarbonate itself induces a signal transduction cascade. Cellular bicarbonate levels reflect intracellular pH as well as CO_2 generation (Bevensee et al., "Control of Intracellular pH," in Seldin, eds., *The Kidney*, Vol. I., Lippincott Williams & Wilkins, Philadelphia, PA. pp. 391–442 (2000), which is hereby incorporated by reference in its entirety); therefore, bicarbonate signaling pathways would respond to a wide variety of cellular transitions. Immunostaining revealed that sAC is present at mitochondria, centrioles, mitotic spindles, and mid-bodies (Zippin et al., "Compartmentalization of Bicarbonate-Sensitive Adenylyl Cyclase in Distinct Signaling Microdomains," *FASEB J.* 17:82–84 (2003), which is hereby incorporated by reference in its entirety), suggesting the existence of multiple cAMP signaling microdomains within a single cell. A remaining challenge will be to determine whether sAC molecules in these different microdomains are subject to independent and unique modes of regulation, permitting a variety of distinct responses independently mediated by the same second messenger.

Example 15 – Soluble Adenylyl Cyclase as the Source of Glucose-Induced cAMP Required for Glucose-Stimulated Insulin Secretion

[0077] Beta-cells of the islets of Langerhans secrete insulin in response to nutrient secretagogues, such as glucose. Despite knowing for over thirty years that glucose-stimulated insulin secretion (GSIS) is accompanied by a rise in the second messenger cAMP (Charles et al., "Adenosine 3',5'-Monophosphate in Pancreatic Islets: Glucose-Induced Insulin Release," *Science* 179:569-571 (1973); Charles et al., "Insulin Secretion. Interrelationships of Glucose, Cyclic Adenosine 3:5-Monophosphate, and Calcium," *J. Biol. Chem.* 250:6134-6140 (1975); Rutter, "Nutrient-Secretion Coupling in the Pancreatic Islet Beta-Cell: Recent Advances," *Mol. Aspects Med.* 22:247-284 (2001), which are hereby incorporated by reference in their entirety), the source of cAMP and its connection to glucose metabolism has remained undefined (Rutter, "Nutrient-Secretion Coupling in the Pancreatic Islet Beta-Cell: Recent Advances," *Mol. Aspects Med.* 22:247-284 (2001), which is hereby incorporated by reference in its entirety). The second messenger is essential for GSIS; membrane permeable cAMP analogs elicit

insulin secretion (Schubart et al., "Cyclic Adenosine 3':5'-Monophosphate-Mediated Insulin Secretion and Ribosomal Protein Phosphorylation in a Hamster Islet Cell Tumor," *J. Biol. Chem.* 252:92-101 (1977), which is hereby incorporated by reference in its entirety), and two of the three known targets of cAMP, PKA and EPAC, are required for normal insulin release. Until recently, G protein regulated tmACs constituted the only known sources of cAMP in beta-cells, but cAMP generated by tmACs is unable on its own to elicit insulin secretion (Rutter, "Nutrient-Secretion Coupling in the Pancreatic Islet Beta-Cell: Recent Advances," *Mol. Aspects Med.* 22:247-284 (2001), which is hereby incorporated by reference in its entirety). tmAC modulation by hormones, such as glucagon and incretins, potentiates glucose-induced insulin secretion, yet constitutive activation of tmACs in beta-cells did not stimulate insulin release in low glucose (Delmeire et al., "Type VIII Adenylyl Cyclase in Rat Beta Cells: Coincidence Signal Detector/Generator for Glucose and GLP-1," *Diabetologia* 46:1383-1393 (2003); Ma et al., "Constitutively Active Stimulatory G-Protein Alpha S in Beta-Cells of Transgenic Mice Causes Counterregulation of the Increased Adenosine 3',5'-Monophosphate and Insulin Secretion," *Endocrinology* 134:42-47 (1994); Rutter, "Nutrient-Secretion Coupling in the Pancreatic Islet Beta-Cell: Recent Advances," *Mol. Aspects Med.* 22:247-284 (2001), which are hereby incorporated by reference in their entirety) nor did it affect glucose tolerance in mice (Ma et al., "Constitutively Active Stimulatory G-Protein Alpha S in Beta-Cells of Transgenic Mice Causes Counterregulation of the Increased Adenosine 3',5'-Monophosphate and Insulin Secretion," *Endocrinology* 134:42-47 (1994), which is hereby incorporated by reference in its entirety).

[0078] An additional source of cAMP in mammalian cells, "soluble" adenylyl cyclase (sAC), has been identified (Buck et al., "Cytosolic Adenylyl Cyclase Defines a Unique Signaling Molecule in Mammals," *Proc. Natl. Acad. Sci. USA* 96:79–84 (1999), which is hereby incorporated by reference in its entirety). sAC activity is regulated by the intracellular signaling molecules bicarbonate (Chen et al., "Soluble Adenylyl Cyclase as an Evolutionarily Conserved Bicarbonate Sensor," *Science* 289:625–628 (2000), which is hereby incorporated by reference in its entirety) and calcium (Jaiswal et al., "Calcium Regulation of the Soluble Adenylyl Cyclase Expressed in Mammalian

Spermatozoa," *Proc. Natl. Acad. Sci. USA* 100:10676–10681 (2003); Litvin et al., "Kinetic Properties of "Soluble" Adenylyl Cyclase. Synergism Between Calcium and Bicarbonate," *J. Biol. Chem.* 278:15922–15926 (2003), which are hereby incorporated by reference in their entirety), both of which are essential for normal glucose-induced insulin release (Parkkila et al., "Expression of Carbonic Anhydrase V in Pancreatic Beta Cells Suggests Role for Mitochondrial Carbonic Anhydrase in Insulin Secretion," *J. Biol. Chem.* 273:24620-24623 (1998); Rutter, "Nutrient-Secretion Coupling in the Pancreatic Islet Beta-Cell: Recent Advances," *Mol. Aspects Med.* 22:247-284 (2001), which are hereby incorporated by reference in their entirety). In contrast to plasma membrane bound tmACs, sAC is localized to intracellular compartments containing cAMP targets (Zippin et al., "Compartmentalization of Bicarbonate-Sensitive Adenylyl Cyclase in Distinct Signaling Microdomains," *FASEB J.* 17:82–84 (2003), which is hereby incorporated by reference in its entirety) where it appears to be the source of locally acting second messenger (Bundey et al., "Discrete Intracellular Signaling Domains of Soluble Adenylyl Cyclase: Camps of cAMP?" *Sci STKE* 2004 (231):pe19 (2004); Zippin et al., "Bicarbonate-Responsive "Soluble" Adenylyl Cyclase Defines a Nuclear cAMP Microdomain," *J. Cell Biol.* 164:527-534 (2004), which are hereby incorporated by reference in their entirety). The data in this example shows that sAC is present in beta-cells and is localized near insulin secretory granules. Proximity to insulin secretory granules and regulation by intracellular signals downstream from glucose metabolism suggested sAC could be a local source of cAMP mediating glucose-elicited insulin secretion. Using small molecule inhibitors which distinguish between sAC and tmACs, sAC was identified as the source of glucose-induced cAMP in beta-cells that is essential for glucose-induced insulin secretion in insulinoma cell lines and isolated islets and for normal glucose homeostasis and insulin secretion in mice.

Cell Culture

[0079] INS-1E cells (passage 140-150) were cultured as previously described in Merglen et al., "Glucose Sensitivity and Metabolism-Secretion Coupling Studied During Two-Year Continuous Culture in INS-1E Insulinoma Cells," *Endocrinology* 145:667-678 (2004), which is hereby incorporated by

reference in its entirety. Briefly, cells were passaged every three days and cultured under 5% CO_2 with RPMI containing 10 mM Hepes, 50 μM β-mercaptoethanol, and 10% FBS. sAC overexpressing stable cell lines were constructed by infecting INS-1E cells with a lentiviral-based vector (Gateway Cloning System, Invitrogen) containing the full length sAC cDNA. Single clones (SF2 and SF5) were selected with blasticidin (1 μg/ml).

Immunocytochemistry

[0080] Sectioned rat pancreas (6 μm), BetaTC6, RINm5F, or INS-1E cells were fixed for 15 minutes in 4% paraformaldehyde, washed, permeabilized in 0.1% Triton X-100, washed, blocked in 2% BSA, and then probed with biotinylated R52 (Zippin et al., "Compartmentalization of Bicarbonate-Sensitive Adenylyl Cyclase in Distinct Signaling Microdomains," *FASEB J.* 17:82–84 (2003), which is hereby incorporated by reference in its entirety), anti-C-term polyclonal (Zippin et al., "Compartmentalization of Bicarbonate-Sensitive Adenylyl Cyclase in Distinct Signaling Microdomains," *FASEB J.* 17:82–84 (2003), which is hereby incorporated by reference in its entirety), or anti-insulin (polyclonal Santa Cruz, H-89 or monoclonal Sigma) overnight. Sections and coverslips were then washed and probed with appropriate secondary antibodies (1:200, Alexafluor, Molecular Probes). Images were recorded on a Nikon microscope.

Adenylyl Cyclase Assays and cAMP Determinations

[0081] *In vitro* adenylyl cyclase assays were performed on purified recombinant human sAC_t protein as previously described in Litvin et al., "Kinetic Properties of "Soluble" Adenylyl Cyclase. Synergism Between Calcium and Bicarbonate," *J. Biol. Chem.* 278:15922–15926 (2003), which is hereby incorporated by reference in its entirety, or on whole cell lysates of INS-1E cells lysed in 50 mM Tris-HCl pH7.5, 0.5 mM EDTA with protease inhibitors. Adenylyl cyclase activity was measured as previously described (Buck et al., "Cytosolic Adenylyl Cyclase Defines a Unique Signaling Molecule in Mammals," *Proc. Natl. Acad. Sci. USA* 96:79–84 (1999); Chen et al., "Soluble Adenylyl Cyclase as an Evolutionarily Conserved Bicarbonate Sensor," *Science* 289:625–

628 (2000), which are hereby incorporated by reference in their entirety). *In vivo* cAMP accumulation was measured in cells pre-incubated in IBMX (0.5 mM) for 10 minutes, followed by the addition of stimuli for 15 minutes. Intracellular cAMP was determined in cells lysed with 0.1 M HCl using Correlate-EIA Direct cAMP Assay (Assay Designs, Inc.).

Pancreatic Islets Isolation

[0082] Islets from C57Bl/6 adult male mice were isolated by digestion of pancreas with Collagenase P and DNase I (Roche Diagnostics, Basel, Switzerland), as described previously in Lacy et al., "Method for the Isolation of Intact Islets of Langerhans From the Rat Pancreas," *Diabetes* 16:35-39 (1967), which is hereby incorporated by reference in its entirety. After several washes with Hank's Balanced Salt Solution, islets were hand-picked and 15-20 islets were distributed into each well of a 12 well plate to adhere overnight in RPMI-1640 media supplemented with 10 mM HEPES, 5.6 mM glucose, 10% FBS, 2 mM L-glutamine, 1 mM sodium pyruvate, and antibiotics.

Insulin Release

[0083] Insulin release in INS-1E cells was performed as previously described in Antinozzi et al. "Mitochondrial Metabolism Sets the Maximal Limit of Fuel-Stimulated Insulin Secretion in a Model Pancreatic Beta Cell: A Survey of Four Fuel Secretagogues," *J. Biol. Chem.* 277:11746-11755 (2002), which is hereby incorporated by reference in its entirety. Briefly, cells (passage 140-150) were plated at 2.5 x 10^5 cells/well in a 24 well plate and permitted to recover for two days. Cells were glucose starved by incubation for 1 hour in the presence of 2.5 mM glucose KRB medium supplemented with 2 mM sodium bicarbonate, 10 mM Hepes, and 0.1% BSA. After washing, cells were incubated in KRB with either 2.5 mM or 16 mM glucose in the presence of either vehicle control (DMSO or MeOH) or indicated drug. After the indicated time, removed media was cleared of cell debris and secreted insulin was measured by Insulin ELISA kit (Linco Research, St. Charles, MO, or ALPCO, Windham, NH). If cAMP was to be concomitantly measured, cells were pre-treated with IBMX for the final 10 minutes of the glucose starvation and IBMX was included in all subsequent

incubations. For the washout experiment, subsequent to initial insulin determination, cells treated with KH7 were placed in fresh KRB (2.5 mM glucose) for an additional hour and insulin release was measured as above in the absence of any added drug. For transferrin recycling, loading of cells with I^{125} transferrin was performed during hour incubation in 2.5 mM glucose KRB. Media was then changed to 2.5 mM glucose KRB with DMSO or KH7 and transferrin recycling measured as previously described in Johnson et al., "A Di-Leucine Sequence and a Cluster of Acidic Amino Acids are Required for Dynamic Retention in the Endosomal Recycling Compartment of Fibroblasts," *Mol. Biol. Cell* 12:367-381 (2001), which is hereby incorporated by reference in its entirety.

[0084] Insulin release from isolated islets was performed in 12 well plates. Islets were preincubated in KRB (2.8 mM glucose) for 1 hour followed by incubation for 30 minutes in 2.8 mM glucose KRB in the presence of drug. The same wells were then incubated for an additional 30 minutes in 16.7 mM glucose KRB in the presence of the same drugs. Media was removed, cleared of cells, and insulin was measured.

Glucose Tolerance

[0085] C57Bl/6 adult male mice were maintained on a 12 hour light/dark cycle, with free access to water and standard laboratory chow (Research Animal Resource Center, Weill Medical College of Cornell University). Animals were treated in accordance with our institutions guidelines. After a 14-16 hour overnight fast with free access to water, blood was removed from the tail vein for glucose (Hemocue B-Glucose Microcuvette and Analyzer; Hemocue, Inc., Lake Forest, CA) and insulin (Rat/Mouse Insulin ELISA Kit; Linco Research) measurements. Mice then received an i.p injection of 100 mM KH7 (100 μmoles/kg) or vehicle control. Twenty minutes later, both groups were injected i.p. with 1 g/kg glucose (20% solution). Blood samples were taken from the tail vein at times indicated, and glucose and insulin were quantitated according to manufacturer's instructions.

sAC as the Source of Glucose-Induced cAMP Required for GSIS

[0086] The mRNA for sAC was detected in insulinoma cell lines including INS-1E cells. To examine protein localization, pancreatic islets and insulinoma cell lines were immunostained with multiple monoclonal and polyclonal antibodies directed against different sAC epitopes. sAC protein was detected throughout the cytoplasm of endocrine and exocrine pancreas and in the nuclei of a subset of islet cells (Figure 7A). Expression in a subset of nuclei is consistent with the observations in liver (see Example 9). Co-staining with insulin (Figure 7A), glucagon, and somatostatin revealed that sAC was not exclusively localized to any specific cell type but was evenly distributed in all cells of the islet. To examine the localization of sAC within insulin secreting beta-cells at higher resolution, sAC in beta-cell lines were immunostained. In BetaTC6 (Figure 7B), RINm5F (Figure 7C), and INS-1E cells (Figure 7D), sAC exhibited a punctate staining pattern throughout the cytoplasm which co-localized with insulin secretory granules (Figures 7B-D). Recent models of cAMP signal transduction depend upon discrete signaling microdomains where the second messenger diffuses only short distances to its targets (Bundey et al., "Discrete Intracellular Signaling Domains of Soluble Adenylyl Cyclase: Camps of cAMP?" *Sci STKE* 2004, pe19 (2004); Rich et al., "Cyclic Nucleotide-Gated Channels Colocalize With Adenylyl Cyclase in Regions of Restricted cAMP Diffusion," *J. Gen. Physiol.* 116:147–161 (2000); Rich et al., "A Uniform Extracellular Stimulus Triggers Distinct cAMP Signals in Different Compartments of a Simple Cell," *Proc. Natl. Acad. Sci. USA* 98:13049–13054 (2001); Zaccolo et al., "Discrete Microdomains With High Concentration of cAMP in Stimulated Rat Neonatal Cardiac Myocytes," *Science* 295:1711–1715 (2002); Zippin et al., "Bicarbonate-Responsive "Soluble" Adenylyl Cyclase Defines a Nuclear cAMP Microdomain," *J. Cell Biol.* 164:527-534 (2004), which are hereby incorporated by reference in their entirety). The observed proximity of sAC to insulin secretory granules, which contain cAMP effector proteins important in insulin release (Ammala et al., "Calcium-Independent Potentiation of Insulin Release by Cyclic AMP in Single Beta-Cells," *Nature* 363:356-358 (1993); Fujimoto et al., "Piccolo, A Ca^{2+} Sensor in Pancreatic Beta-Cells. Involvement of cAMP-GEFII.Rim2.Piccolo Complex in

cAMP-Dependent Exocytosis," *J. Biol. Chem.* 277:50497-50502 (2002); Holz, "EPAC: A New cAMP-Binding Protein in Support of Glucagon-Like Peptide-1 Receptor-Mediated Signal Transduction in the Pancreatic Beta-Cell," *Diabetes* 53:5-13 (2004); Kang et al., "EPAC-Selective cAMP Analog 8-pCPT-2'-O-Me-cAMP as a Stimulus for Ca^{2+}-Induced Ca^{2+} Release and Exocytosis in Pancreatic Beta-Cells," *J. Biol. Chem.* 278:8279-8285 (2003); Ozaki et al., "cAMP-GEFII is a Direct Target of cAMP in Regulated Exocytosis," *Nat. Cell. Biol.* 2:805-811 (2000); Renstrom et al., "Protein Kinase A-Dependent and -Independent Stimulation of Exocytosis by cAMP in Mouse Pancreatic B-Cells," *J. Physiol.* 502 (Pt 1):105-118 (1997); Shibasaki et al., "Interaction of ATP Sensor, cAMP Sensor, Ca^{2+} Sensor, and Voltage-Dependent Ca^{2+} Channel in Insulin Granule Exocytosis," *J. Biol. Chem.* 279:7956-7961 (2004), which are hereby incorporated by reference in their entirety), suggested that sAC generated cAMP could participate in insulin secretion.

[0087] To distinguish between sources of cAMP in mammalian cells, a cadre of small molecules capable of differentiating between the two classes of adenylyl cyclases, G protein responsive tmACs and bicarbonate (Chen et al., "Soluble Adenylyl Cyclase as an Evolutionarily Conserved Bicarbonate Sensor," *Science* 289:625–628. (2000), which is hereby incorporated by reference in its entirety) and calcium responsive sAC (Jaiswal et al., "Calcium Regulation of the Soluble Adenylyl Cyclase Expressed in Mammalian Spermatozoa," *Proc. Natl. Acad. Sci. USA* 100:10676–10681 (2003); Litvin et al., "Kinetic Properties of "Soluble" Adenylyl Cyclase. Synergism Between Calcium and Bicarbonate," *J. Biol. Chem.* 278:15922–15926 (2003), which are hereby incorporated by reference in their entirety) were applied. P site inhibitors are a family of small molecules, predominantly adenosine analogs, which potently inhibit tmACs (IC_{50} = 3-16 μM) (Johnson et al., "Isozyme-Dependent Sensitivity of Adenylyl Cyclases to P-site-Mediated Inhibition by Adenine Nucleosides and Nucleoside 3'-Polyphosphates," *J. Biol. Chem.* 272:8962-8966 (1997), which is hereby incorporated by reference in its entirety). P site inhibitors are significantly less potent towards sAC (Gille et al., "Differential Inhibition of Adenylyl Cyclase Isoforms and Soluble Guanylyl Cyclase by Purine and Pyrimidine Nucleotides," *J. Biol. Chem.* 279:19955-19969 (2004), which is hereby incorporated by reference in its entirety), and it was

determined that 2'5' dideoxyadenosine (2'5'ddAdo) did not significantly affect sAC at concentrations up to 300 μM (Figures 8A-C). A dearth of highly selective sAC inhibitors usable in cellular contexts led to the screening of a combinatorial chemical library for small molecules capable of inhibiting sAC (see Example 11 and Table 1). A compound, KH7, which potently inhibited sAC (Figure 9A) and was inert towards tmACs (Figure 9C), was identified. A structurally similar compound, KH7.15, was inert towards both sAC (Figure 9B) and tmACs (Figure 9C) and is useful as a negative control.

[0088] Incubation in low glucose (i.e., 2.5 mM) elicits a basal level of insulin secretion from INS-1E cells (Merglen et al., "Glucose Sensitivity and Metabolism-Secretion Coupling Studied During Two-Year Continuous Culture in INS-1E Insulinoma Cells," *Endocrinology* 145:667-678 (2004), which is hereby incorporated by reference in its entirety), whereas incubation in high glucose (i.e., 16 mM) led to an elevated level of insulin release (Figures 10A-F). This increased insulin release is termed glucose-stimulated insulin secretion (GSIS). KH7 dose dependently inhibited GSIS with an IC_{50} (~ 5 μM) (Figure 10A) similar to its potency on purified sAC protein (Figure 9A: IC_{50} ~3 μM). KH7 blocked all insulin release induced by high glucose, while the structurally related, inert KH7.15 did not affect insulin secretion (Figure 10B). In the presence of KH7, no significant insulin release was observed up to 45 minutes after addition of high glucose. A structurally unrelated, noncompetitive inhibitor of sAC, 2-hydroxyestradiol (CE) (Braun, "Inhibition of the Soluble Form of Testis Adenylate Cyclase by Catechol Estrogens and Other Catechols," *Proc. Soc. Exp. Biol. Med.* 194:58-63 (1990); Pastor-Soler et al., "Bicarbonate-Regulated Adenylyl Cyclase (sAC) is a Sensor That Regulates pH-Dependent V-ATPase Recycling," *J. Biol. Chem.* 278:49523–49529 (2003), which are hereby incorporated by reference in their entirety), also completely inhibited GSIS (Figure 10B and Figure 11). Furthermore, specific inhibition of tmACs by P site inhibitors did not have any significant affect on insulin release (Figure 10B); therefore, cyclase specific inhibition revealed that sAC is the only adenylyl cyclase required for GSIS.

[0089] It was genetically confirmed that sAC is required for GSIS, using RNA*i* knockdown. Transfection of two distinct sAC-specific RNA*i*

oligonucleotides reduced sAC protein levels (Figure 12A, insert) and blunted GSIS (Figure 12B).

[0090] Concomitant with its induction of insulin secretion, glucose elicits a rise in intracellular cAMP in beta-cells (Charles et al., "Adenosine 3',5'-Monophosphate in Pancreatic Islets: Glucose-Induced Insulin Release," *Science* 179:569-571 (1973); Charles et al., "Insulin Secretion. Interrelationships of Glucose, Cyclic Adenosine 3:5-Monophosphate, and Calcium," *J. Biol. Chem.* 250:6134-6140 (1975); Rutter, "Nutrient-Secretion Coupling in the Pancreatic Islet Beta-Cell: Recent Advances," *Mol. Aspects Med.* 22:247-284 (2001), which are hereby incorporated by reference in their entirety). sAC-specific RNA*i* (Figure 12A), KH7 or 2-hydroxyestradiol, but not KH7.15 (Figure 10C), blocked the cAMP induced by the presence of high glucose. As with insulin secretion (Figure 10A), KH7's IC_{50} for blocking glucose-induced cAMP matched its dose response of sAC inhibition (Figure 9A). Although inert towards GSIS (Figure 10B), P site inhibitor partially decreased glucose-induced cAMP generation (Figure 10C). This decrease is consistent with inhibition of tmAC type VIII, known to be present in beta-cells and previously shown to be responsive to glucose-induced elevations of calcium (Delmeire et al., "Type VIII Adenylyl Cyclase in Rat Beta Cells: Coincidence Signal Detector/Generator for Glucose and GLP-1," *Diabetologia* 46:1383-1393 (2003), which is hereby incorporated by reference in its entirety). However, as confirmed below, tmAC-generated cAMP is ineffective at initiating insulin secretion (Delmeire et al., "Type VIII Adenylyl Cyclase in Rat Beta Cells: Coincidence Signal Detector/Generator for Glucose and GLP-1," *Diabetologia* 46:1383-1393 (2003); Ma et al., "Constitutively Active Stimulatory G-Protein Alpha S in Beta-Cells of Transgenic Mice Causes Counterregulation of the Increased Adenosine 3',5'-Monophosphate and Insulin Secretion," *Endocrinology* 134:42-47 (1994); Rutter, "Nutrient-Secretion Coupling in the Pancreatic Islet Beta-Cell: Recent Advances," *Mol. Aspects Med.* 22:247-284 (2001), which are hereby incorporated by reference in their entirety).

[0091] In cells, cAMP levels are determined by their synthesis via adenylyl cyclases and their breakdown via phosphodiesterases (PDE). Therefore, the ability of the global PDE inhibitor IBMX to increase cAMP levels is dependent upon the presence of an active cyclase. IBMX enhanced GSIS at least

2 fold in INS-1E cells (Figure 10D), but in contrast to exogenously added, membrane permeable cAMP analogs (Figure 10E), IBMX treatment did not restore GSIS in the presence of KH7 inhibition (Figure 10D). Thus, IBMX could not rescue GSIS in the absence of a source of second messenger, confirming that the sole source of glucose-induced cAMP capable of initiating insulin release is KH7 sensitive sAC.

[0092] The ability of KH7 to block both cAMP generation and insulin secretion was not due to cellular toxicity; the cells appeared healthy, and inhibition was specific, selective, and reversible. Insulin release induced by the phorbol ester PMA was unaffected by KH7 (Figures 13A-B), and KH7 inhibition of GSIS was rescued by addition of a membrane-permeable cAMP analog (Figure 10E). These data show that the transduction pathways essential for insulin release were still functional in KH7 treated cells. Sixty minutes following removal of drug (i.e., drug "washout"), normal GSIS was restored, demonstrating that there were no significant, long-lasting changes induced by KH7 treatment. Finally, transferrin recycling (Johnson et al., "A Di-Leucine Sequence and a Cluster of Acidic Amino Acids are Required for Dynamic Retention in the Endosomal Recycling Compartment of Fibroblasts," *Mol. Biol. Cell* 12:367-381 (2001), which is hereby incorporated by reference in its entirety) in INS-1E cells was unaffected by KH7 (Figure 13B) or CE; therefore, inhibition of sAC did not have pleiotropic effects on general vesicular trafficking to the cell surface.

[0093] To establish the role of sAC inhibitors in a more native beta-cell preparation, experiments were performed to investigate whether these small molecules would affect GSIS in primary mouse islets. KH7 (Figure 10F) and CE inhibited insulin release induced by high glucose in mouse primary islets.

sAC-Generated cAMP is Sufficient to Elicit Insulin Secretion

[0094] The genetic and pharmacological inhibitor studies revealed that sAC-generated cAMP is necessary for GSIS; next, it was demonstrated that, distinct from tmAC-generated cAMP, sAC-generated cAMP was sufficient to elicit insulin secretion. Consistent with published reports (Delmeire et al., "Type VIII Adenylyl Cyclase in Rat Beta Cells: Coincidence Signal Detector/Generator for Glucose and GLP-1," *Diabetologia* 46:1383-1393 (2003); Ma et al.,

"Constitutively Active Stimulatory G-Protein Alpha S in Beta-Cells of Transgenic Mice Causes Counterregulation of the Increased Adenosine 3',5'-Monophosphate and Insulin Secretion," *Endocrinology* 134:42-47 (1994); Rutter, "Nutrient-Secretion Coupling in the Pancreatic Islet Beta-Cell: Recent Advances," *Mol. Aspects Med.* 22:247-284 (2001), which are hereby incorporated by reference in their entirety), in low glucose, stimulation of tmACs by hormones, i.e., glucagon (Figure 14A) or GLP-1, elicited a three fold increase in cAMP generation, but led to no significant increase in insulin release (Figure 14A). In contrast, stable overexpression of sAC in INS-1E cells (Figure 14B, inset) elevated both intracellular cAMP and insulin secretion even in low glucose (Figure 14B). This sAC overexpression-induced increase in insulin release was inhibited by KH7 and sAC overexpression potentiated GSIS in a KH7 dependent manner (Figure 14C). Therefore, sAC generated cAMP is distinct from tmAC-generated cAMP; tmAC generated cAMP is only capable of modulating GSIS (Delmeire et al., "Type VIII Adenylyl Cyclase in Rat Beta Cells: Coincidence Signal Detector/Generator for Glucose and GLP-1," *Diabetologia* 46:1383-1393 (2003); Rutter, "Nutrient-Secretion Coupling in the Pancreatic Islet Beta-Cell: Recent Advances," *Mol. Aspects Med.* 22:247-284 (2001), which are hereby incorporated by reference in their entirety), while sAC generated cAMP is uniquely capable of initiating insulin secretion by itself.

sAC Inhibition Induces a Diabetes-Like Phenotype in Mice

[0095] The observed role of sAC in insulin release in an animal was confirmed by performing a glucose tolerance test on mice injected with KH7 or with vehicle control. Mice injected with KH7 were glucose intolerant as compared to mice injected with vehicle alone (Figure 15A); blood glucose reached higher levels after KH7 injection. Furthermore, whereas a glucose challenge elicited the expected increase in serum insulin levels in control mice, no statistically significant glucose-induced insulin release was detected at any time following glucose challenge in mice injected with KH7 (Figure 15B). KH7 did not appear to be toxic to the mice. Injection of KH7 (as well as vehicle control) did not elicit any behavior or stressful responses inconsistent with a simple saline injection. Complete anatomical, histological, and blood post-mortem analysis

(performed within 48 hours after drug treatment) revealed no significant toxicology or histological pathology associated with a single injection of KH7. There were no long-term pancreatic effects due to a single KH7 injection. One week after mice were injected with KH7 and displayed delayed glucose tolerance and blunted insulin release, these same mice (n=2) exhibited a normal glucose tolerance and insulin response in a glucose tolerance test in the absence of further drug. Therefore, a sAC specific inhibitor which blocked GSIS in cell lines and primary islets elicited a transient diabetes-like phenotype in mice.

[0096] In summary, it is likely that sAC senses intrinsic cellular signals originating from glucose metabolism (Zippin et al., "CO(2)/HCO(3)(-)-Responsive Soluble Adenylyl Cyclase as a Putative Metabolic Sensor," *Trends Endocrinol. Metab.* 12:366–370 (2001), which is hereby incorporated by reference in its entirety) to initiate cAMP-dependent pathways essential for GSIS. In contrast, tmACs are responsible for the cAMP-dependent potentiation of GSIS (Delmeire et al., "Type VIII Adenylyl Cyclase in Rat Beta Cells: Coincidence Signal Detector/Generator for Glucose and GLP-1," *Diabetologia* 46:1383-1393 (2003); Rutter, "Nutrient-Secretion Coupling in the Pancreatic Islet Beta-Cell: Recent Advances," *Mol. Aspects Med.* 22:247-284 (2001), which are hereby incorporated by reference in their entirety). The role of sAC as a glucose sensor in beta-cells raises the possibility that it also senses nutritional availability in other physiological systems. Consistent with this hypothesis, conservation of bicarbonate-responsive sAC-like cyclases from bacteria (Cann et al., "A Defined Subset of Adenylyl Cyclases is Regulated by Bicarbonate Ion," *J. Biol. Chem.* 278:35033-35038 (2003); Chen et al., "Soluble Adenylyl Cyclase as an Evolutionarily Conserved Bicarbonate Sensor," *Science* 289:625–628. (2000), which are hereby incorporated by reference in their entirety) and unicellular eukaryotes (Roelofs et al., "Deducing the Origin of Soluble Adenylyl Cyclase, A Gene Lost in Multiple Lineages," *Mol. Biol. Evol.* 19:2239-2246 (2002), which is hereby incorporated by reference in its entirety) suggest that this class of cyclase represents an evolutionarily conserved mechanism for sensing environmental cues such as pH and nutritional availability. In contrast, G protein-regulated tmACs are first documented in the social amoeba Dictyostelium (Pitt et al., "Structurally Distinct and Stage-Specific Adenylyl Cyclase Genes Play Different Roles in

Dictyostelium Development," *Cell* 69:305-315 (1992), which is hereby incorporated by reference in its entirety), and therefore, seem to have arisen concomitant with the need for intercellular communication.

[0097] This study also demonstrates the strategic use of adenylyl cyclase selective inhibitors to identify sAC as the source of cAMP mediating GSIS. Their use constitutes a general paradigm for differentiating between sAC and tmACs as the originator of this ubiquitous second messenger implicated in a wide variety of physiological processes.

[0098] Diseases whose predisposing factor is a pathologically uncontrolled release of insulin (e.g., insulinoma or persistent hyperinsulinemic hypoglycemia) can lead to life threatening episodes of hypoglycemia possibly resulting in stroke, organ failure, or even death. With its transient effects on insulin release and lack of toxicity, KH7 represents a potential therapeutic for the treatment of hyperinsulinemia or hypoglycemia. Finally, because sAC is important for normal glucose-stimulated insulin secretion and glucose homeostasis in mice and because overexpression of sAC is sufficient to elicit insulin secretion, sAC activators may represent a new class of diabetes therapeutics.

Example 16 – Inhibition of *Plasmodium falciparum* sAC-like Adenylyl Cyclase – A New Mechamism for a Malaria Antibiotic

[0099] The causative agent of malaria, *Plasmodium falciparum*, expresses two adenylyl cyclase genes (Muhia et al., "Multiple Splice Variants Encode a Novel Adenylyl Cyclase of Possible Plastid Origin Expressed in the Sexual Stage of the Malaria Parasite *Plasmodium falciparum*," *J. Biol. Chem.*, 278(24):22014-22022 (2003), which is hereby incorporated by reference in its entirety), which were both postulated to be bicarbonate responsive based upon the presence of a predictive threonine residue (Muhia et al., "Multiple Splice Variants Encode a Novel Adenylyl Cyclase of Possible Plastid Origin Expressed in the Sexual Stage of the Malaria Parasite *Plasmodium falciparum*," *J. Biol. Chem.*, 278(24):22014-22022 (2003); Cann et al., "A Defined Subset of Adenylyl Cyclases is Regulated by Bicarbonate Ion," *J. Biol. Chem.*, 278(37):35033-35038 (2003), which are hereby incorporated by reference in their entirety). One gene, PfACb, conforms

to the mammalian sAC structure; it possesses two catalytic domains related to C1 and C2 of mammalian sAC, followed by a consensus P loop sequence (Muhia et al., "Multiple Splice Variants Encode a Novel Adenylyl Cyclase of Possible Plastid Origin Expressed in the Sexual Stage of the Malaria Parasite *Plasmodium falciparum*," *J. Biol. Chem.*, 278(24):22014-22022 (2003), which is hereby incorporated by reference in its entirety). The other, PfACa, is most similar to single domain cyanobacterial adenylyl cyclases. However, both differ significantly from the amino acid sequence of mammalian sAC, suggesting that PfAC selective inhibitors can be developed.

[0100] The dependence upon CO_2/bicarbonate for culturing *Plasmodium falciparum* (Trager et al., "Human Malaria Parasites in Continuous Culture, *Science*, 193(4254):673-675 (1976), which is hereby incorporated by reference in its entirety) and the identification of two sAC-like adenylyl cyclases predicted to be bicarbonate responsive (Muhia et al., "Multiple Splice Variants Encode a Novel Adenylyl Cyclase of Possible Plastid Origin Expressed in the Sexual Stage of the Malaria Parasite *Plasmodium falciparum*," *J. Biol. Chem.*, 278(24):22014-22022 (2003), which is hereby incorporated by reference in its entirety) suggested that bicarbonate regulation of one (or both) of these cyclases may be essential for viability. It can be reasoned that the sAC inhibitor, KH7, which was found to inhibit sAC-like adenylyl cyclases from evolutionarily distant organisms including, mammals, Chloroflexus, Cyanobacteria, and Candida, should also inhibit the sAC-like PfAC cyclases. Therefore, the effect of sAC inhibitors on *P. falciparum* viability was tested. Using a viability assay based on the luminescence of a strain of *P. falciparum* engineered to express luciferase, it was demonstrated that infectious growth (i.e., in red blood cells) was rapidly (in a single generation) and potently affected by KH7 (Figure 16A). The most likely molecular target of KH7 in *P. falciparum* are the sAC-like PfAC cyclases. The ability of KH7 to inhibit adenylyl cyclase activity in whole cell extracts of isolated parasites was confirmed. Following the procedure of Read and Mikkelsen, "*Plasmodium falciparum*-Infected Erythrocytes Contain an Adenylate Cyclase with Properties Which Differ from the Host Enzyme," *Molecular & Biochemical Parasitology*, 45:109 (1991), which is hereby incorporated by reference in its entirety, for isolating parasites and specifically assaying parasite adenylyl cyclase

activity, it was demonstrated that KH7 displayed equal dose responses at killing parasites and at inhibiting PfAC activity (Figure 16B). These data strongly support the hypothesis that at least one of the PfAC genes is essential for viability and represents a novel target for malaria therapeutics. In addition, it was found that the compound used as a negative control in mammalian contexts, KH7.15, displayed a 10-fold lower affinity for killing *P. falciparum* and for inhibiting PfAC activity relative to KH7. Therefore, because KH7.15 does not inhibit mammalian sAC yet does inhibit PfACs and is lethal to parasites, it provides proof-of-principle that PfAC inhibitors can be developed which distinguish between mammalian and plasmodium sAC-like adenylyl cyclases. Since relative high doses of KH7.15 ($\geq$100 μM) are required to inhibit PfAC activity and kill parasites, there is a likelihood for other side effects, unrelated to mammalian sAC. Thus, it would be advantageous to identify a drug that will kill *P. falciparum* in mammalian blood, while having little, if any, inhibitory effect on mammalian sAC and biological effects on the human host that are mediated by mammalian sACs. KH7 or KH7.15 are suitable lead compounds for development of a new PfAC inhibitor that will kill PfAC selectively and thus provide an avenue to the eradication of the malaria parasite within mammalian systems.

Example 17 – Inhibition of *Candida albicans* sAC-like Adenylyl Cyclase – A New Mechamisn for a *Candida albicans* Antibiotic

[0101] *Candida albicans* is the most common opportunistic fungal pathogen of humans accounting for up to 60% of Candida species isolated from cases of infection. The increase in the numbers of patients in the high-risk category, i.e., those requiring long-term in-dwelling catheters, broad-spectrum antibiotic therapy, and treatment for cancer have all contributed to the escalation in the prevalence of serious *Candida* infections. *Candida albicans* expresses a sAC-like adenylyl cyclase gene and exhibits a strong dependence upon carbon dioxide (and bicarbonate, the activator of sAC-like adenylyl cyclases) for differentiation into the infectious part of its life cycle.

[0102] The catalytic portion of the sAC like adenylyl cyclase from *Candida albicans* (fragment JR3) was cloned, expressed, and purified, and experiments were performed, showing that the JR3 fragment was bicarbonate

responsive and KH7 sensitive. Figure 17A illustrates the bicarbonate dependence of the JR3 fragment; bicarbonate stimulated the adenylyl cyclase activity with an EC_{50} of approximately 0.2 mM. Figure 17B illustrates the KH7 sensitivity of the JR3 fragment; the sAC inhibitor, KH7, inhibited the expressed and purified candida sAC-like adenylyl cyclase with an IC_{50} of approximately 23 μM. KH7 also dose dependently inhibited the CO_2 induced differentiation into the filamentous, infectious stage with similar dose dependency.

Example 18 – Role of sAC in NGF-Induced Rap1 Activation

[0103] Neurotrophic factors, or *neurotrophins*, are a family of proteins whose principal functions include promoting differentiation and survival of multiple neuronal subtypes in the central and peripheral nervous systems. Recently, alterations in neurotrophin-mediated signaling have been implicated in the progression of several devastating neurodegenerative diseases. In particular, studies in cell and animal models have identified nerve growth factor (NGF), the most studied member of the neurotrophin family, as a key player in the pathogeneses of Alzheimer's disease (AD), amyotrophic lateral sclerosis (ALS), and peripheral neuropathies (Dichter et al., "Nerve Growth Factor-Induced Increase in Electrical Excitability and Acetylcholine Sensitivity of a Rat Pheochromocytoma Cell Line," *Nature*, 268:501-504 (1977), which is hereby incorporated by reference in its entirety).

[0104] One of the most widely *used* systems for dissecting the biology of NGF is the pheochromocytoma PC12 cell line; upon treatment with NGF, PC12 cells differentiate into sympathetic-like neurons. Among the early steps known to be in this signaling pathway is the activation of the small G protein Rap1. Interestingly, both phenomena, neuronal differentiation and Rap1 activation, can be induced by cell-permeable analogues of cAMP (Heidemann et al., "Synergistic Effects of Cyclic AMP and NGF on Neurite Outgrowth and MT Stability of PC 12 Cells," *J. Cell Biol.*, 916-927 (1985); Vossler et al., "cAMP Activates MAP Kinase and Elk-1 Through a B-Raf and Rap1-Dependent Pathway," *Cell*, 89(1):73-82 (1997), which are hereby incorporated by reference in their entirety). Also like NGF, cAMP has been found to be essential for axonal regeneration after nerve injury and associated with neurodegenerative processes (Dubus et al.,

"Expression of Trk Isoforms in Brain Regions and in the Striatum of Patients With Alzheimer's Disease," *Exp. Neurol.*, 165(2):285-294 (2000); Salehi et al., "Alzheimer's Disease and NGF Signaling," *J. Neural Trans.*, 111:323-345 (2004); Turner et al., "Effect of p75 Neurotrophin Receptor Antagonist on Disease Progression in Transgenic Amyotrophic Lateral Sclerosis Mice." *J. Neurosci. Res.*, 78:193-199 (2004), which are hereby incorporated by reference in their entirety). These findings suggest a link between NGF and the second messenger; however, the mechanism leading from NGF to cAMP has never been described.

[0105] The sAC-specific inhibitor, KH7, was found to block NGF induced Rap1 activation (Figure 17), suggesting that sAC is required for NGF induced Rap1 activation. Rap1 activation can be *restored* by addition of exogenous cAMP, confirming that KH7 is likely to mediate its effects solely via inhibition of sAC. These data demonstrate that sAC is an integral signaling protein in the differentiation and survival of neurons, and suggest that sAC may prove to be a novel therapeutic target for the treatment of AD, ALS or peripheral neuropathies.

[0106] Although the invention has been described in detail, for the purpose of illustration, it is understood that such detail is for that purpose and variations can be made therein by those skilled in the art without departing from the spirit and scope of the invention which is defined by the following claims.